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Improving geotechnical properties using paper ash and olive pomace

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Abstract

Soil stabilization techniques play a crucial role in improving soil quality, reducing construction costs, and addressing environmental and mechanical challenges encountered in civil engineering. Faced with low-quality soils, several researchers have explored innovative solutions by using natural waste materials. New approaches are being developed to recover local waste and reuse it in civil engineering applications, particularly in earthworks. In this study, the goal is to experimentally compare the impact of two types of waste on the stabilization of clay soils, by testing different percentages (2%, 4%, 6%, 8%) through various laboratory tests, such as compressive strength, shear strength, and oedometer compression test. The results obtained are analyzed to evaluate the effectiveness of these wastes in soil treatment. The preliminary study conducted on the clay soil showed a significant improvement in its mechanical properties, which could enhance its stability and bearing capacity.

Keywords: recovery, industrial waste, stabilization, agricultural waste

1 Introduction

Materials recovery is a key approach to sustainable resource management, as it enables waste to be recycled to extract materials that can be reused in various sectors. The choice of waste materials to be recycled depends mainly on their abundance, availability, and potential for use in specific applications, particularly in civil engineering.

Through an in-depth literature review, we have identified the effectiveness of various additives on the geotechnical properties of soils. Agricultural or industrial waste can be converted into soil reinforcement additives [1]. This type of modification is particularly beneficial in civil engineering applications, where soil workability and stability are essential for infrastructure projects.

The work in [2] used ash from burnt olive waste as a material to stabilize bentonite clay, with proportions ranging from 1% to 10% by weight. Test results showed a decrease in the plasticity index, reducing the deformability of the soils, making them less plastic and therefore easier to

handle. Similar results were obtained by the authors in [3], who demonstrated that 3% olive pomace ash was sufficient to stabilize expansive soil.

The authors in [4] studied the use of olive waste in the form of burnt ash to improve the geotechnical properties of soils. Their research showed that the addition of 2.5% by weight of this ash significantly increased the unconfined compressive strength and maximum dry density of the soil. This improvement translates into better soil compactness, meaning that particles are more densely agglomerated, reducing voids in the soil structure. The increase in compactness also leads to an improvement in compressive strength, an essential parameter for the stability and durability of infrastructure built on this type of soil.

The authors [5] conducted an experiment on soft sandy-clay soil to examine the effect of ash from waste paper sludge on the mechanical behavior and microstructure of the soil. The tests were carried out with mixtures containing between 2% and 16% ash by weight. The results showed that the best mechanical performance, particularly in terms of shear strength and compressive strength, was obtained with the addition of 10% ash. At this proportion, significant changes in the soil microstructure were observed, including the formation of new cementitious agents acting as binders. These agents strengthen the interactions between soil particles, improving the overall stability of the mixture.

For their part, the authors [6] explored a combination of calcined paper sludge and cement as a soil stabilizing material. Their study revealed that this mixture considerably improves the bearing capacity of the soil, making it better able to support heavy loads.

In the study by [7], it was highlighted that the use of calcined paper sludge as an additive offers an alternative and effective solution for improving the geotechnical properties of soils, even surpassing commonly used materials such as lime and cement. This finding is particularly important in the context of soil stabilization for construction or infrastructure projects.

In addition, the improvement in soil densification, measured by the increase in the CBR (California Bearing Ratio) value, is a key indicator of the effectiveness of the additives. The authors [8, 9] used paper ash to treat soils with different percentages. They employed nanostructured waste paper ash as an additive to improve the geotechnical properties of lateritic soil, conducting a series of standardized tests. A significant increase in the CBR value was observed, and the compressive strength increased with a 28-day curing time, ensuring durability. They concluded that paper ash is an excellent soil strength enhancer, particularly for sub-base materials used in pavement construction.

The authors [10] found that the use of paper ash to reduce soil swelling produced promising results, demonstrating the effectiveness of this addition in soil stabilization. In fact, an 80% reduction in swelling is a crucial factor in improving the mechanical properties and stability of soils.

Integrating these materials into the stabilization process is an innovative approach that not only improves the geotechnical properties of clay soils but also promotes more sustainable management of local waste.

2 Materials

2.1. Clay soil: The soil used in this study consists of 80% treated Kaolin extracted from the Soalka company and 20% Bentonite, marketed by the Bental company. From an experimental

point of view, the use of this soil offers the advantage of providing a swelling reference soil with uniform geotechnical properties for all the tests.

Table 1: physico-mechanical properties of soil [10]

Parameters	Values
Optimum content moisture (%)	20,20
Maximum dry density (t/m^3)	1,55
Cohesion(Bar)	0,2
Angle of friction ($^{\circ}$)	4.57
Compression index (%)	31.5
Swelling index(%)	11
Compressive strength (Mpa)	0.259

Mineralogical analysis was carried out at the emerging materials research unit in Sétif. The reference soil components show that mostaganem bentonite contains montmorillonite as an abundant phase, followed by illite. Quartz and calcite, while Tamazert kaolin contains an intense peak of kaolinite, quartz and muscovite. For the reference soil, the appearance of an intense peak corresponding to quartz, kaolinite, muscovite, also the appearance of illite.

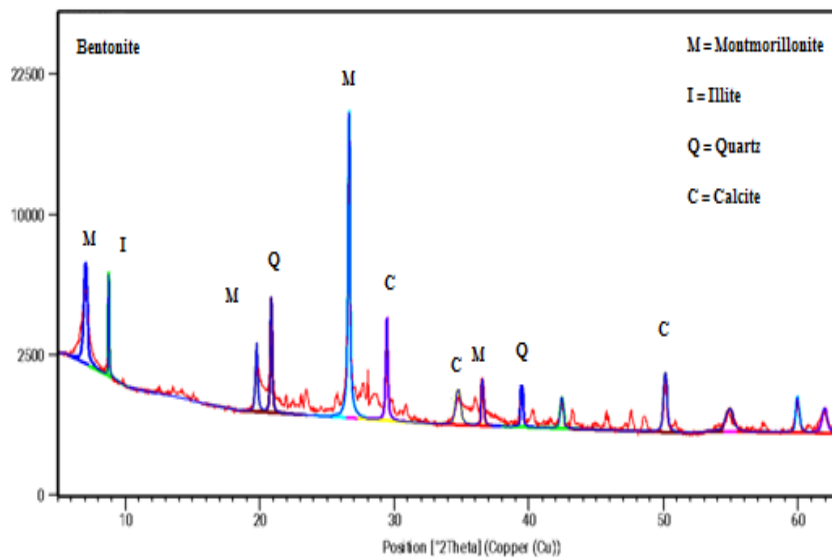


Figure 1: Mineralogical analysis of Mostaganem Bentonite

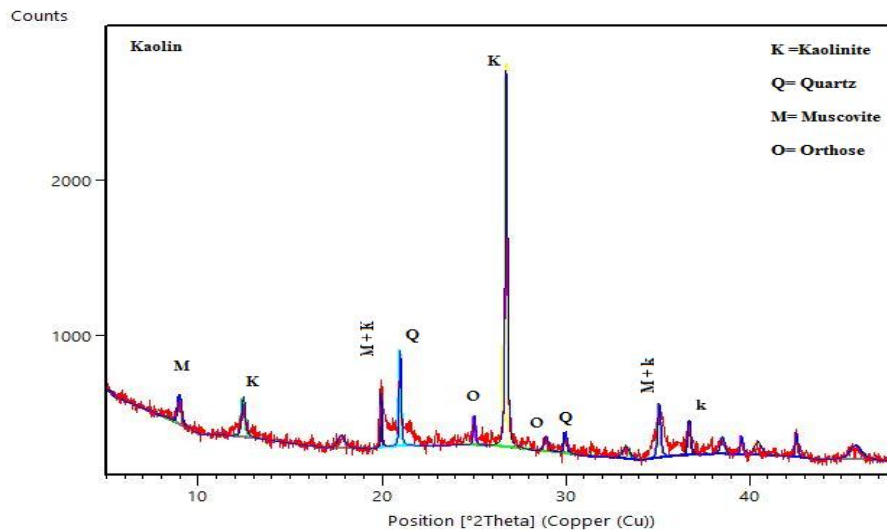


Figure 2: Mineralogical analysis of processed kaolin 2

Microstructural analysis of the reference soil using scanning electron microscopy (SEM) revealed a characteristic organisation of the clays present. The observations reveal the presence of dispersed sheets, typical of clays with a lamellar structure, distributed randomly. The sheets have a scaly structure, which is mainly due to the presence of kaolinite, the main clay mineral in the mixture. This scaly structure is due to the specific morphology of kaolinite, characterised by fine, flattened platelets, [11].

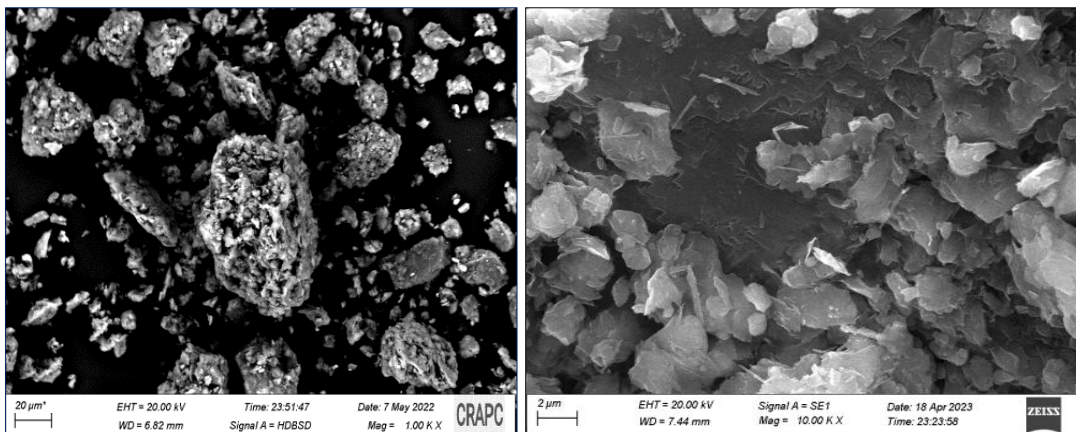


Figure 3: SEM analysis of the reconstructed soil at different magnifications

2.2 Wastes: Our work consists of selecting several types of waste in different forms (powders, grains) to determine which form offers the best performance for soil stabilization. The choice of wastes was based on their local availability, low cost, and ecological potential. Among these wastes, paper ash and olive pomace were selected because of their specific properties and their compatibility with improving the physical and chemical properties of soils. The chemical and mineralogical analyses carried out on these materials support the use of these wastes in soil stabilization for the following reasons: the rigidity provided by olive pomace and the high calcium content in paper ash, which favors the formation of bonds between the addition

and the components of the soil. The incorporation percentages of these wastes were determined based on laboratory tests and the analysis of existing works.

2.2.1. Paper ash:

Paper ash is obtained by incinerating waste paper. The process involves collecting the waste and then burning it at high temperatures, reducing the paper to ash. The temperature and duration of combustion can influence the chemical and mineralogical composition of the ash. In our work, we used office paper subjected to an average temperature of 600°C. Once combustion is complete, the ash is cooled, sieved to remove impurities, and sometimes ground to obtain a fine, homogeneous powder ready for use in soil stabilization tests.

The mineralogical and chemical composition of the ash varies according to the type of paper used, the combustion process, and the temperature applied.

Chemical analysis shows that paper ash is rich in lime (CaO), with a content of 86.3%, a key component in soil stabilization processes. This reacts with clay particles and water to form cementitious compounds such as hydrated calcium silicate (C-S-H) and hydrated calcium aluminate (C-A-H), which improve the geotechnical properties of soils.

Table 2: Chemical analysis of soils used by XRF (x-ray fluorescence) [10]

Oxydes	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	TiO ₂	Na ₂ O	SO ₃
Pourcentages	4.58	1.74	86.3	2.07	0.977	0.16	1,14	4.58

XRD analysis of paper ash powder enabled us to determine the different crystalline phases. Lime (CaO) represents the major phase of the ash, followed by Gehlenite (Ca₂Al₂SiO₇), Mayenite (Ca₁₂Al₁₀O₄₀) and Calcite (CaCO₃) with traces of Portlandite (Ca(OH)₂) and Hatrurite (Ca₄Al₃O₁₂). The results of this XRD analysis corroborate those obtained in a previous study conducted by [7], he reported the appearance of Belite (Ca₂SiO₄) and Quartz (SiO₂), suggesting a possible variation in mineralogical composition depending on combustion conditions or paper sources.

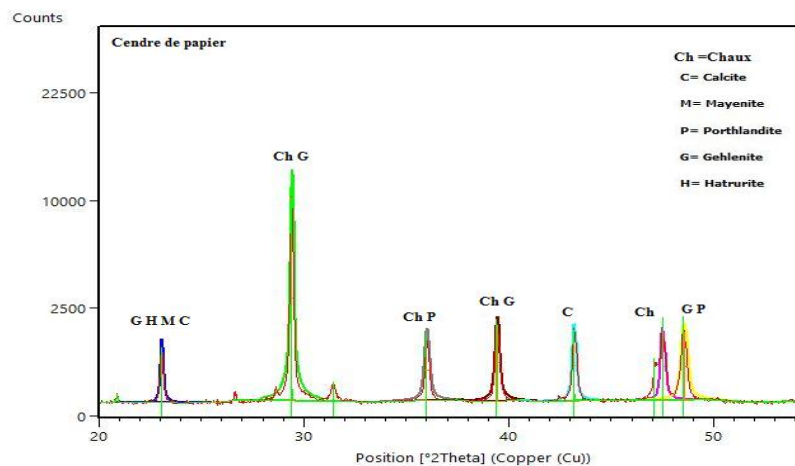


Figure 4:DRX of paper ash

SEM scanning electron microscopy shows a fibrous structure, suggesting that paper ash consists mainly of fibers. These fibers may originate from the cellulose present in the paper. Furthermore, the presence of particles between the fibers suggests that there are elements other than the fibers themselves in the composition of the ash. These particles could be additives present in the paper, or elements derived from paper combustion.

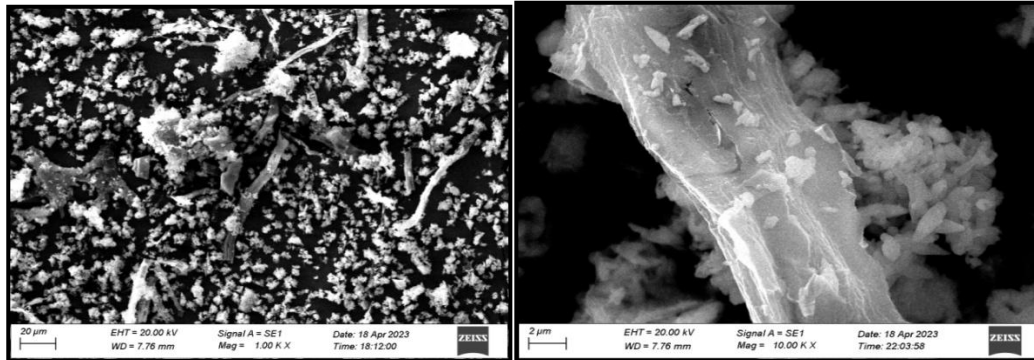


Figure 5: Microstructural analysis of paper ash at different magnifications

2.2.2. Olive pomace: It is a by-product of the olive oil extraction process, consisting of skins, pulp residues, and stone fragments. The olive pomace used in this study comes from oil mills in the commune of Sidi Abdelaziz, in the wilaya of Jijel, before being used as an additive for soil stabilization. The pomace must be dried to reduce its moisture content. Since pomace is rich in organic matter, drying is essential to prevent undesirable effects such as excessive biological degradation (composting) [12].

This preparation ensures better preservation of the pomace and improves its performance as an additive for soil stabilization



Olive trees

Olive pomace

Table 3: EDX results on olive pomace

Chemical elements	Si	Al	Ca	Fe	K	Mg	O	C	Cu
% by mass	7.48	5.21	2.88	2.26	1.05	0.51	40.04	39.69	0.87

The EDX results showed the most important chemical elements by mass to be carbon (C) and oxygen (O). These results agree with those obtained [13] which showed the appearance of two

peaks. Olive pomace, rich in organic carbon, can have a beneficial effect on soil structure, increasing tensile strength and stability.

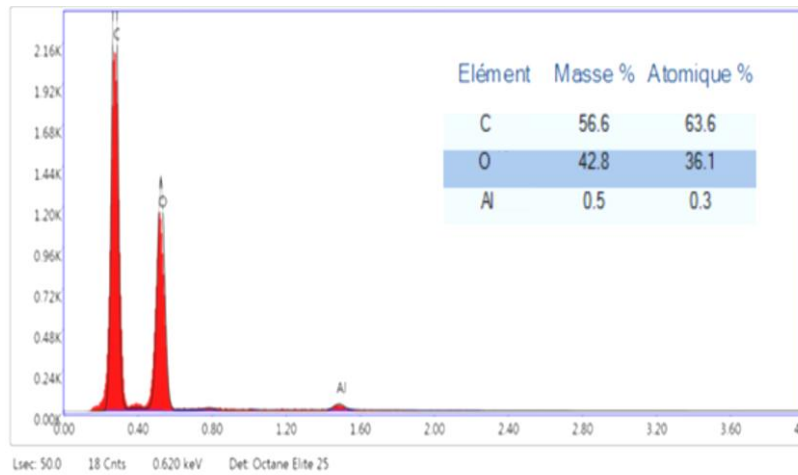


Figure 6: Energy of dispersion by x-rays of olive pomace (EDX)

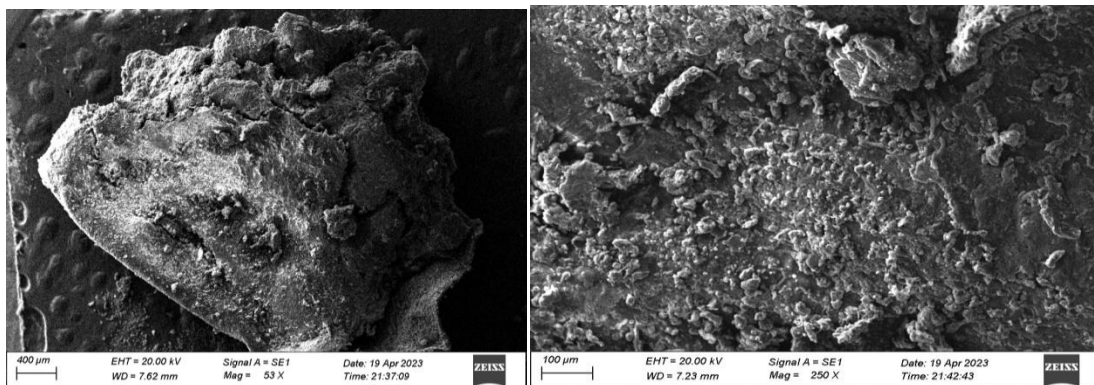


Figure 7: SEM of olive pomace

Microstructural analysis of olive pomace has revealed a complex and heterogeneous morphology. This structural diversity testifies to the rich characteristics of the pomace, which presents a varied range of structures and compositions visible at different scales, from the microscopic to the macroscopic.

Observations also revealed the presence of hollow cavities, which could be attributed to natural voids formed during processing or drying. These cavities, combined with a rough surface, are the direct result of the presence of plant fibres. These fibres, made up mainly of cellulose (32.7%), hemicellulose (16.2%) and lignin (30.6%) [14] contribute to the irregular texture and give the pomace its specific mechanical properties.

This unique microstructure could influence the functional properties of olive pomace, such as its adsorption capacity, its mechanical characteristics or its potential for soil reinforcement applications.

3 Methods

In order to study the effectiveness of olive pomace and paper ash in stabilising clay soils, we launched an experimental programme based on a series of standard tests. Firstly, a mixture of soil and additions was prepared with different percentages of 2%, 4%, 6% and 8% by weight of soil (Figure 8 and Figure 9).

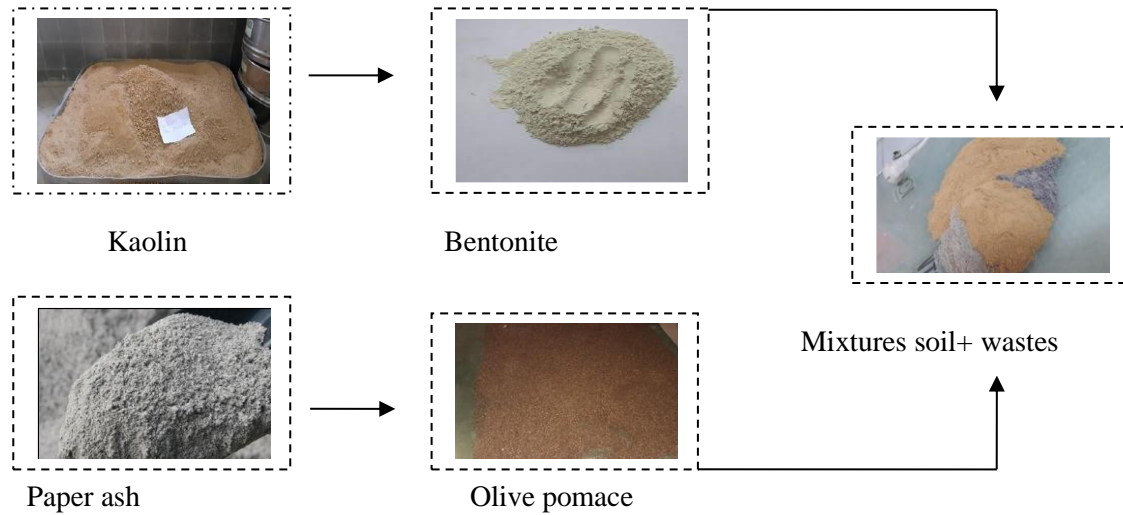
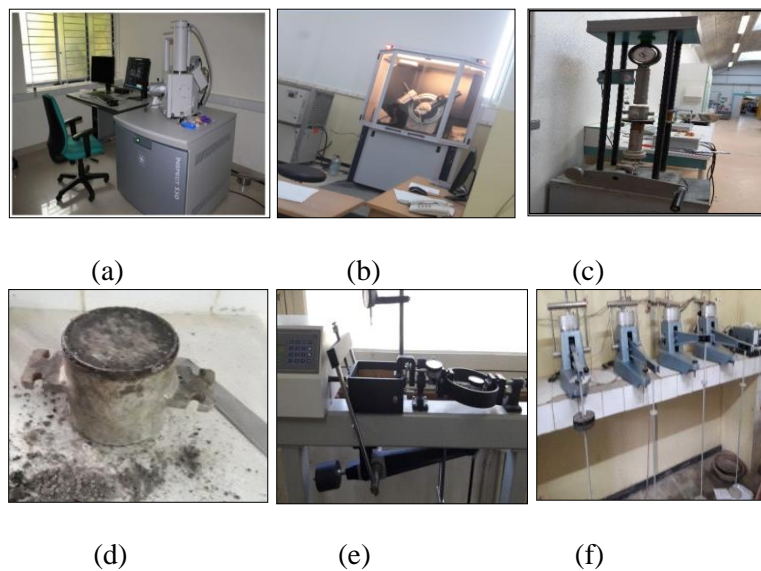


Figure 8: Materials used



- (a) SEM microstructural analysis
- (b) Mineralogical analysis by DRX
- (c) Compressive strength test according to the NF P 94-093 standard.
- (d) Compaction test according to the NF P 94-093 standard.
- (e) Direct shear test according to the NF P 94-071-1 standard.
- (f) Compressibility test according to the standard (XP P 94-090--1).

Figure 9: Geotechnical tests performed in this study

4 Results and discussion

4.1. Behaviour of paper ash and olive pomace on soil microstructure:

The SEM results show a significant change in the morphology of the reconstituted soil particles treated with ash, compared with the reference soil. This change is characterised by a rearrangement of the soil particles, indicating the influence of the ash on the overall structure of the soil. As the ash penetrates the soil matrix, it begins to fill the pores between the grains, resulting in the formation of chemical or physical bonds that act as binders. These binders improve the cohesion between soil particles, resulting in a reduction in the number of pores.

Reducing the number of pores is particularly important because it increases the density of the soil and reduces its porosity. This gives the soil greater mechanical stability, which is essential for many geotechnical applications, particularly in the construction of foundations and infrastructure. In addition, the positive effect of ash on soil microstructure is reflected in an increase in soil strength, as the ash acts in a similar way to a cement binder, consolidating the soil structure while improving its load-bearing capacity.

SEM analysis also reveals that the addition of ash imparts a porous appearance to the surface of the treated soil, suggesting that the ash may play a role in water absorption. However, this aspect requires further investigation in future studies.

Regarding the impact of olive pomace, the SEM results indicate a distinct mechanical effect. Olive pomace, as an organic material, appears to enhance the ductility of the soil, making it more flexible and less prone to fracture under mechanical loads. This improvement in ductility is particularly beneficial in geotechnical applications, as it allows the soil to deform without breaking, which is essential in environments subject to variable movements or pressures.

In addition to improving ductility, the incorporation of olive pomace modifies the surface of soil grains, facilitating the formation of bonds between particles. This surface modification may also influence water retention and circulation within the soil, which could have significant implications for agricultural or environmental applications.

Moreover, olive pomace seems to increase the coarseness of the soil, impacting its texture. A coarser soil, characterized by larger particles and improved aeration, can enhance permeability and drainage. This is particularly advantageous for preventing waterlogging in overly compacted soils. Such changes in texture are valuable for agricultural soil management or soil improvement in civil engineering projects, especially in contexts where erosion resistance and effective rainwater management are critical concerns.

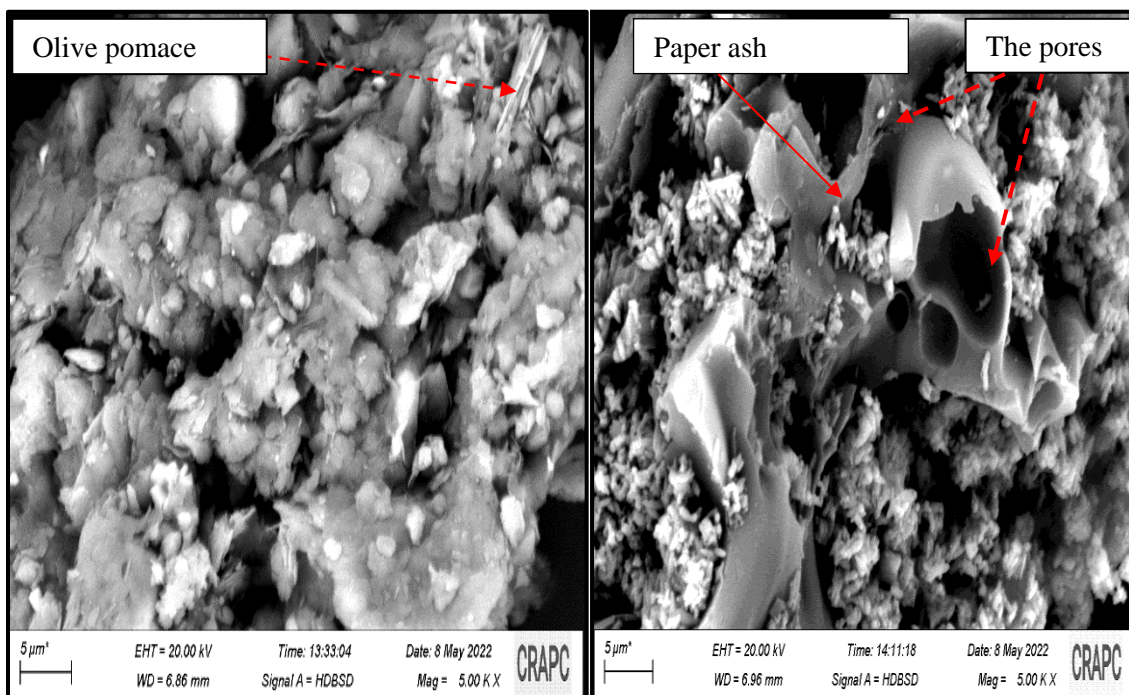


Figure 10: Effect of paper ash on the microstructure of reconstituted soil

4.2. Effect of paper ash and olive pomace on soil mechanical parameters:

We examine the results of incorporating olive pomace and paper ash on soil behaviour. All the results are shown in the following table:

Table 4: Results of paper ash on mechanical parameters

%	Compressive strength	Angle of friction	Cohesion	Swelling index	Compression index
0%	259	4.57	20	11	31
2%	270	7	8	9.4	30.2
4%	300	13	64	7.4	21.2
6%	363	11	39	7	19.8
8%	376	15	50	5.5	19.9

Table 5: Results of olive pomace on mechanical parameters

%	Compressive strength	Angle of friction	Cohesion	Swelling index	Compression index
0%	259	4.57	20	11	31
2%	270	5.2	62	11.9	33
4%	280	6.27	79	10.5	29.8
6%	300	14	90	8.1	28.1
8%	340	21	55	5.1	18.1

4.2.1. Compressive strength

The compressive strength of the natural soil is initially measured at around 0.259 MPa. However, after treatment, a significant increase in compressive strength is observed. In fact, the compressive strength of soil treated with paper ash increases by around 40% compared with untreated soil, rising from 0.259 MPa to 0.376 MPa, and from 0.259 MPa to 0,340 MPa for soil treated with olive pomace. This significant improvement in compressive strength testifies to the effectiveness of the treatment applied to the soil, making it better able to support higher loads and resist deformation under stress.

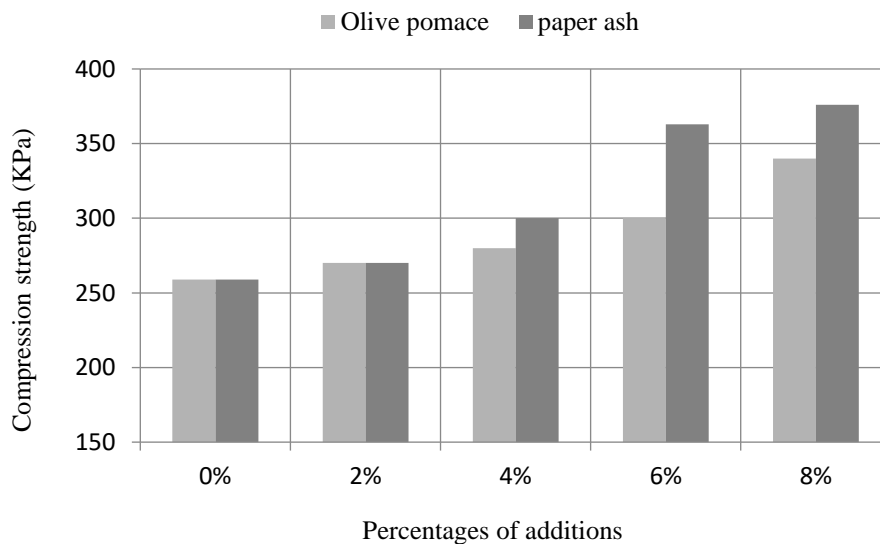


Figure 11: The effect of additions on compression resistance

4.2.2. Shear strength

The Cohesion increases as the percentage of paper ash increases, rising from 20 kPa to 64 kPa for 4% addition, after which it falls to 39 kPa and then rises to 54 kPa. The angle of friction gradually increases from 4.5° to 11°. The improvement in mechanical properties is due to the filling of the pores by the paper ash.

The Cohesion treated with olive pomace showed a significant increase, from 20 kPa for the untreated soil to 90 kPa for the reconstituted soil treated with an addition of 6%. Thereafter, cohesion decreased slightly to 55 kPa. In general, a trend of gradual and continuous increase was observed for the angle of friction, rising from 4.57° to 21°. This increase testifies to a significant improvement in the soil's ability to resist shear stresses.

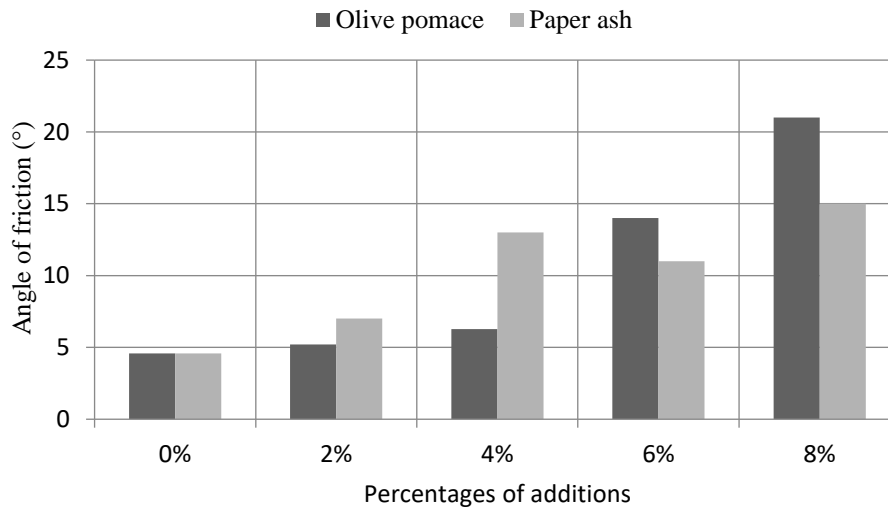


Figure 12: The Effect of additions on the angle of friction of the soil

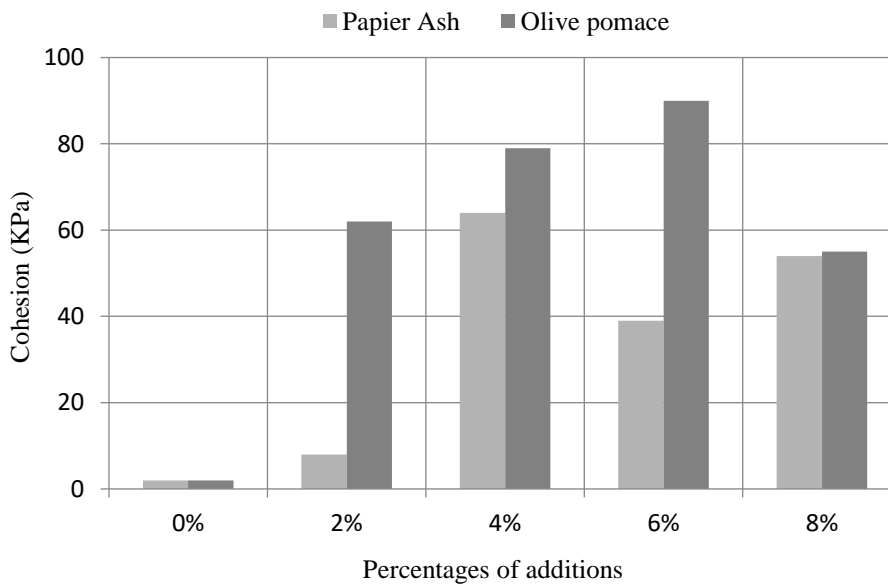


Figure 13: The effect of additions on soil cohesion

4.2.3. Oedometer compression

As the percentage of paper ash increases, the swelling and compression indices of the soil progressively decrease. Increasing the addition of paper ash leads to a progressive decrease in the swelling index, from 11% for the reference soil to just 5.5% for an addition of 8% paper ash. The compression index falls from 31% for the untreated soil to just 19% for the addition of 8% paper ash. This reduction indicates a decrease in the soil's susceptibility to expansion in the presence of water and means that the treated soil is less likely to undergo excessive settlement under load, which may help to improve its stability and load-bearing capacity.

With the initial addition of 2% olive pomace, a slight increase in the compression and swelling indices was observed, but these values then gradually decreased until they were reduced by around half.

Olive pomace significantly reduced the swelling index from 11% to 5.5%. Similarly, the compression index also fell, from 31% to 18%. These results indicate a significant improvement in the geotechnical properties of the soil following the addition of olive pomace. This reduction in the compression and swelling indices suggests a reduction in the soil's susceptibility to excessive deformation under load or in the presence of water.

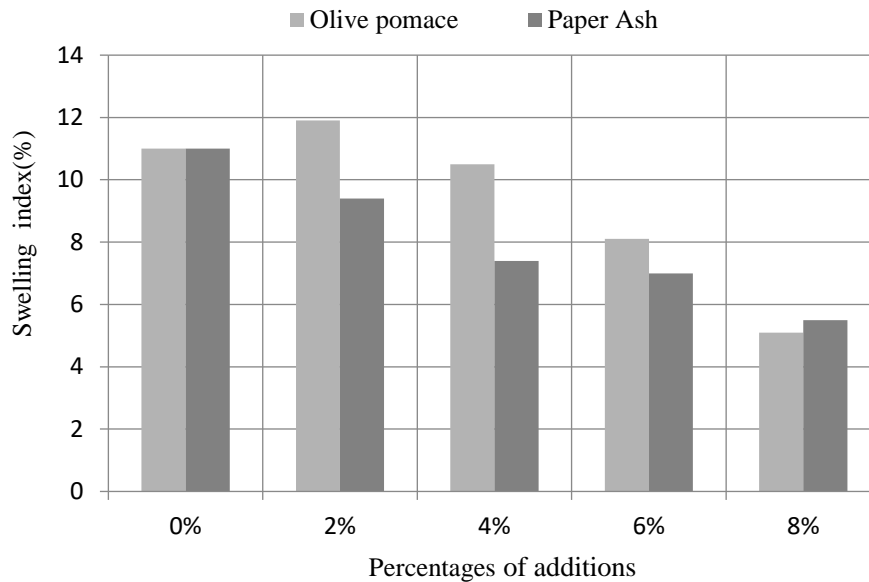


Figure 14: The effect of additions on the swelling index

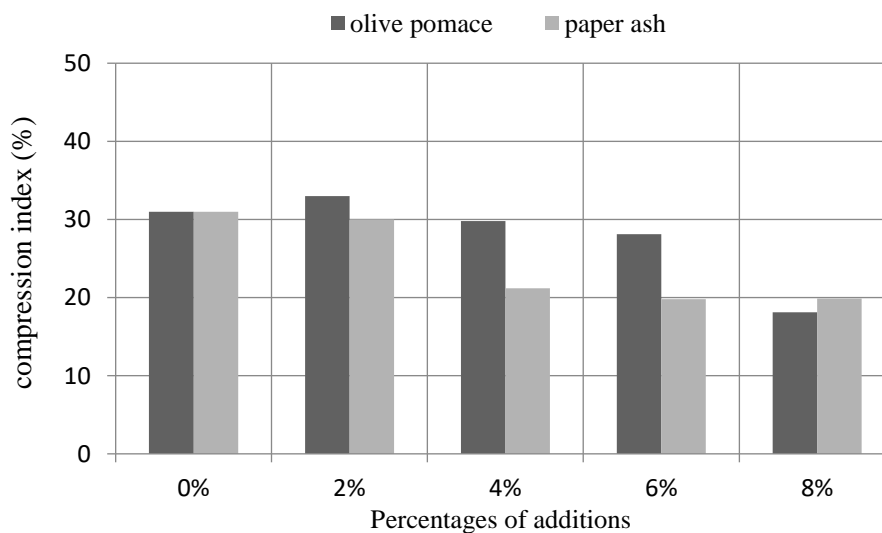


Figure 15: The effect of additions on the compression index

5 Conclusion

Incorporating paper ash into soils is an effective method for improving their geotechnical properties. The ash acts as a stabilizing material, enhancing the soil's resistance to vertical loads (compression) and horizontal forces (shear). Clay soils, which are particularly prone to swelling when absorbing water, benefit significantly from this addition. Paper ash reduces the ability of soil particles to retain water, thereby decreasing their swelling potential.

On a microstructural level, the chemical interaction between paper ash and soil components results in the formation of binders, such as cementitious compounds. These binders reduce the size and quantity of pores in the soil, enhancing overall cohesion and minimizing deformation caused by moisture

This approach is an innovative solution for stabilizing soils and improving their mechanical performance, while mitigating the risks associated with their sensitivity to water

The incorporation of olive pomace into soils is an innovative approach to improving their physico-chemical and mechanical properties, thereby enhancing their stability and performance under different conditions. The addition of olive pomace helps to reduce susceptibility to swelling by limiting the expansion of clay particles.

By altering the internal structure of the soil, olive pomace enhances the shear and compression parameters, thereby strengthening the soil's resistance. This modification improves cohesion between soil particles, increasing overall strength. Furthermore, by modifying the microstructure, olive pomace reduces pore size and increases the apparent density of the soil

These additions are currently regarded as a short-term solution for specific applications, such as stabilizing construction site runways or facilitating the temporary passage of heavy machinery.

Future research will focus on:

- **Studying long-term behavior:** This includes evaluating the resistance of stabilized soils to freeze-thaw cycles, prolonged humidity, and repeated mechanical stress.
- **Durability:** It is essential to determine whether these temporary solutions can be made durable, particularly for applications in sustainable infrastructure.

This work paves the way for the increased use of alternative and recycled materials in soil engineering, fostering a more sustainable and cost-effective approach

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Water Management: Insights from Two Distinct Sub-Saharan Africa

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Abstract

Water management seeks the optimal solutions to the challenges posed by society's demand for food security, energy production, socioeconomic advancement, and sound ecosystems. In the 21st century, the complexities of natural disasters and human-induced factors impede the ability to address water security issues. Sub-Saharan Africa is at a critical juncture where it must implement substantial reforms in the planning and management of its water systems to enhance the sustainability of its water resources. Yet, the region faces numerous water-related issues due to complex natural disasters and human factors such as urbanization and population growth, particularly in countries like Ethiopia and Mauritania. This paper delves into the availability, sustainability, management, and governance of water in these two regions of Horn Africa (Ethiopia) and Western Africa (Mauritania). It also highlights the practices involved in planning, managing, and utilizing water systems and services in these areas. Therefore, this paper provides a foundation for further research and the development of sustainable water resources management in the region.

Keywords: sub-Saharan Africa; water resources; water security; climate change; sustainability

1 Introduction

Water is a fundamental element of life, and it represents a shared legacy with diverse functions, applications, and roles [1,2]. It is also limited in quantity, susceptible to pollution, and subject to the impacts of climate fluctuations, thereby casting doubt on its future accessibility. Similarly, the whole life on planet Earth relies on water systems to sustain food security, energy generation, socioeconomic development, and sound ecosystems. Furthermore, these resources are considered as central to natural environment sustainability and ecological ecosystem evolution.

Globally, the prosperity of communities relies significantly on effectively utilizing water as a valuable resource [3]. The availability and management of these resources significantly influence a nation's prosperity and the well-being of its society. However, with recent rapid industrialization and rapid population increases, the availability and sustainable management of this precious natural resource compromised [4]. On the other hand, concerns about whether there is adequate quantity and quality of water resources to meet societal needs have increasingly become uncertain in recent decades. Especially, with the challenges posed by climate change, complex natural disasters, anthropogenic factors (Figure 5), and the rising demand for this resource have hindered efforts to address water issues [3].

This situation is particularly notable in Sub-Saharan African (SSA) countries [5] such as Ethiopia and Mauritania. The combination of rapid population growth and unplanned urbanization in SSA, coupled with high climate variability, underscores the critical importance of addressing water challenges [6]. The region is notably deficient in access to water supply and sanitation, as highlighted by [7]. Consequently, issues such as increased water pollution, depletion of water resources, ecosystem degradation, and socioeconomic and environmental factors pose significant threats to the region's progress toward water security.

In recent years, complex natural disasters (Figure 5) such as drought, flood, hurricane, have been witnessed on all continents, affecting vast regions the world [8,9]. Among them, Sub-Saharan Africa has recently witnessed exhausting challenges like water scarcity and drought. The region has experienced the worst impacts of climate change, resulting in a significant decline in an annual total precipitation, water scarcity, drought and in some other places flood in the last two decades. This is becoming more severe particularly in western and horn of Africa including Mauritania and Ethiopia.

Water security entails the sustainable and consistent availability of sufficient and acceptable quality water to meet the needs of both human populations and ecosystems, while mitigating potential risks [10]. It involves ensuring the long-term protection of water resources to support current and future generations. Water scarcity arises from an imbalance between water supply and demand in a given geographical area. This issue is particularly pressing in developing countries, especially in Sub-Saharan Africa (SSA), where rapid population growth and climate change are exacerbating water stress. According to [11], under current climate conditions, approximately 50% of the global population in around 50 countries, including those in SSA, could face water stress or scarcity within the next 20 years.

In response to the various water-related challenges facing humanity, the United Nations General Assembly (UNGA) established the Sustainable Development Goals (SDGs) in 2015, with SDG 6—ensuring the availability and sustainable management of water and sanitation for all—as a primary objective [12]. Among responses to such challenges, this paper highlights availability, sustainability, policies and regulations, management and governance of water resources in the two SSA regions. Consequently, in a rapidly changing world, the management of water resources in the Sub-Saharan Africa regions of Ethiopia and Mauritania must prioritize addressing key challenges to achieve SDG and sustainable water resource management in particular.

There are only a few studies that address more than one region of Africa so far as ascertained from the literature. Similarly, there is no exhaustive study covering the two SSA regions. Therefore, this paper aims to address some of these gaps. Thus, here the paper contributes to the sharing of experience emphasizing water availability, management, and governance in two distinct SSA regions, presenting the case of Ethiopia, and Mauritania and finally proffering substantial remarks. It is hoped that these lessons will shed light on water resources management and help the two countries and other sub-Saharan Africa to ensure sustainable water management and SDGs particularly goal 6 (Clean Water and Sanitation) and goal 13 (Climate Action).

The two study regions constitute the sub-Saharan Africa in eastern and western Africa where the paper highlights main challenges. The challenges of water management vary from region to region [13,14], but the nature of prospective solutions to water-related challenges remains the same for different regions, including the two regions (Ethiopia horn of Africa and Western region Mauritania). Therefore, this paper addresses availability, sustainability, challenges, governance and management of water resources in the two regions. In these contexts, this paper makes a novel contribution to the literature on availability, dimensions, regulations, governance and management of water resources in two regions. The lessons learned from the paper include:

- Exploring up to date approaches for sustainable planning and management of water resources to achieve sustainable use of water resources in the two regions
- Addressing the two regions water issues, policies and regulation mechanisms to improve water sustainable planning and demonstrate how one country could learn from the experiences of the other
- Demonstrate lessons learned and put out a comprehensive, consistent, forward-looking on water resources management in Ethiopia, Mauritania, and the rest of SSA regions

2 Materials and Methods

For this article, a comprehensive literature review has been conducted to encompass Water Management: Insights from Two Distinct Sub-Saharan Africa. Sub-Saharan regions, including densely populated countries like Ethiopia and arid desert climate countries such as Mauritania, are striving to find sustainable solutions to water-related issues. This paper's content is based on an extensive literature review that consolidates key research findings on water resources management in Sub-Saharan Africa.

With a focus on Ethiopia, representing one of the most populous countries in Sub-Saharan Africa characterized by highland and sub-tropical regions with relatively abundant water resources, and Mauritania, which exemplifies the water scarcity issues faced by arid and semi-arid regions in Sub-Saharan Africa, providing insights into water management practices in water-scarce environment. Thus, the paper facilitates discussions aimed at improving water management and governance for sustainable development, illustrating how one country can learn from the experiences of the other.

The study was designed to be exploratory, involving content analysis and analyzing data from legislative, administrative and hydrographic areas. Initially, the study focused on two Sub-Saharan regions representing extreme scenarios: non-arid Ethiopia and arid Mauritania, both

affected by complex natural disasters and human factors. The primary data sources were mainly obtained from official agencies in both countries, supplemented by other sources. The data on water resource availability and status in these regions were sourced from the AQUASTAT database, an information system managed by the Food and Agriculture Organization (FAO). The results are presented in tables and figures to illustrate the findings.

The Federal Democratic Republic of Ethiopia, situated in the Horn of Africa (Figure 1), has a population exceeding 125 million [15]. It shares borders with Eritrea and Djibouti to the north, Somalia to the east, Kenya and Somalia to the south, and Sudan and South Sudan to the west. Ethiopia spans an area of 1,127 km², with a water area of 7,444 km² and varying altitudes from 4,550m (Ras Dejan Mountain) to 125m (Dalol Depression) below sea level [16].

Mauritania is a country located in the west of the African continent (Figure 1). The country borders with Western Sahara, Morocco, and the Saharan Democratic Arab Republic, Algeria, Mali and Senegal and bounded on the west by the Atlantic Ocean. Mauritania having a population exceeding 5 million is a water-poor country located partly within the Sahara Desert, receiving very little rainfall [17]. Only the coastal regions of the country receive significant seasonal rainfall. Despite being a water poor nation, in 2000, the country was also one of the world's largest water consumers, with more than 5000 m³ per capita (Figure 3). The total available freshwater resources (surface and groundwaters) were estimated at about 11.5 billion m³ and the total withdrawal water for domestic, agricultural, and industrial purposes (Figure 2) is estimated as 1.7 billion m³ [18].



Figure 1. The geo-referenced map of the two regions (Ethiopia and Mauritania) showing its location on the globe in the Eastern and Western of Africa, indicated in Green

3 Results and discussions

3.1 Availability, sustainability, management and governance of water resources in the two regions

The intricacy of water as a multidimensional strategic resource has been widely debated in many parts of the world [19]. The sustainable management of water resources has thus become a core topic of debate stemming from complex natural disasters and human induced factors, the two regions experiencing enormous challenges in water security. Water availability pertains to the physical quantity of water that is accessible for use in a given region or system. It is influenced by factors such as climate, precipitation, surface water flows, groundwater reserves, and seasonal variations [20]. While water may be physically available in some areas, its usability can be constrained by factors like pollution, salinity, inaccessibility, salinity, inaccessibility, poor infrastructure and unsustainable management.

The global water availability is finite, and Africa, being one of the most populous and driest continents, faces particular challenges in this regard [21]. Africa is the second driest continent in the world after Australia, and the most populous continent in the world after Asia [22,23]. The continental annual average water availability per capita is 4,008 m³/person /year, very low below the global average of 6,498 m³ [24]. The continent represents only 9 percent of global freshwater resources, whereas 15 percent of the global population.

In SSA, the lack of access to potable drinking water, a prevalent issue. According to Nkiaka et al.,[7] who assessed SSA using the Water–Energy–Food (WEF) Nexus Index tool, indicates suboptimal performance, with countries in the West African sub-region of Mauritania performing worst. Across SSA, 69 percent of the population lacks adequate sanitation and hygiene facilities, and 40 percent are without access to clean water and the availability of improved sanitation facilities stands at about 18% [25]. For example, in Ethiopia, approximately half of its population has no access to safe drinking water services, while only 14% having access to safely managed drinking water [23]. Conversely, relatively with its smaller population Mauritania boasts a higher level of access to basic drinking water services at about 78%, with 65% of the population having improved sanitation facilities and 87% having access to improved drinking water sources [26,27].

Moreover, both the availability and distribution of water vary significantly across the continent [28], thus leading to economic imbalances, poor governance, and institutional failures. Some regions have an abundance of water while others struggle with severe shortages. For example, in areas such as Sub-Saharan Africa, specifically in arid and semi-arid region of Mauritania and some areas of Ethiopia chronic water shortages are prevalent. As opposed to East and Northwestern areas, the central African region and southern parts relatively possess ample waters.

Ethiopia naturally possesses abundant water resources that could meet domestic needs, provided sufficient financial resources are allocated for water resources development [29]. Owing to its geographical location and favorable climate, the country gets relatively high rainfall. However, more than 80% of the country's water resources are found only in the four major basins which contain no more than one third of the country's population [16, 29]. Furthermore, in recent

years, there has been a significant decrease in precipitation, making the country likely to face challenges in achieving water and food security due to the dramatic effects of climate change. Geographically Mauritania is located in one of the regions mostly affected by complex disasters in sub-Saharan Africa. Natural calamities such as climate change, temperature increase and rainfall variability accelerating depletion of water resources in the region [30]. The sum of total renewable groundwater and renewable surface water resources (both internal and external) is estimated as 11.4 billion m³ per year [31,32].

With a total annual water withdrawal of nearly 6 billion cubic meters (BCM), Ethiopia faces moderate to high water stress, projected to increase by 2040 to 0.55, indicating high water stress due to population growth and climate change impacts [11, 18]. Similarly, Mauritania classified as a water-scarce country, with a water stress index of 0.85 [33, 34] indicating very high-water stress projected to remain high, necessitating urgent use of innovative water technologies alongside traditional water management practices, provides a balanced approach to addressing water scarcity. Therefore, improved water use efficiency such as smart irrigation system and investment in infrastructure are essential to address water issues and enhance sustainable development.

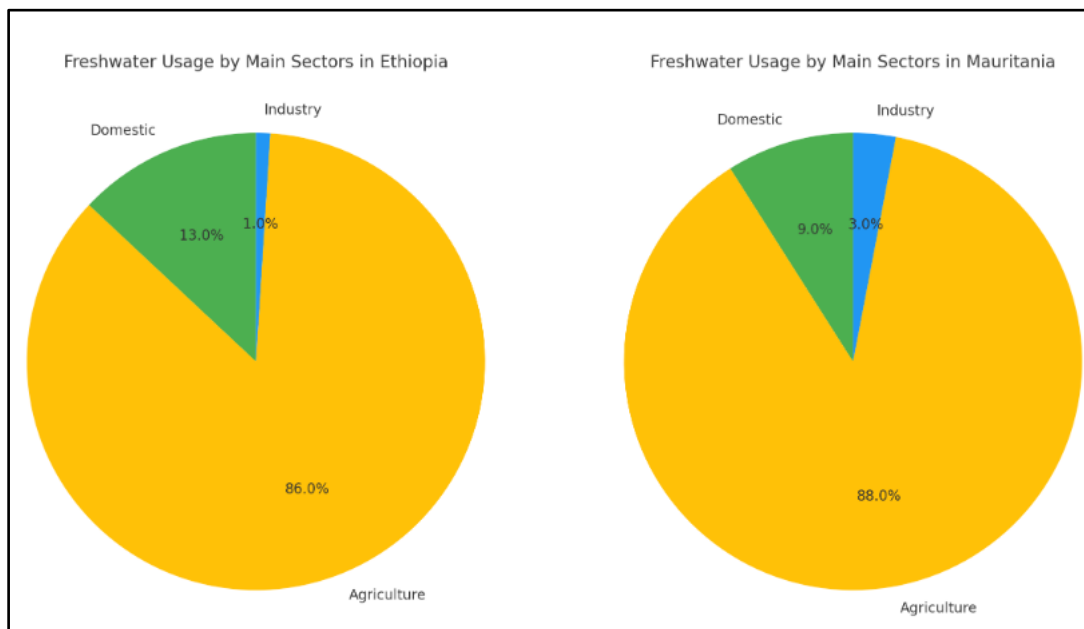


Figure 2. The two countries' freshwater allocation for domestic, agriculture and industry [23,33]

The above figure illustrates that the agricultural sector is the largest water consumer in both countries. In both regions, more than 85% of the water allocation is used for agricultural purposes, which is notably above the global average of 70%. Likewise, the following figure 3 reveals concise water resources per capita in the two regions.

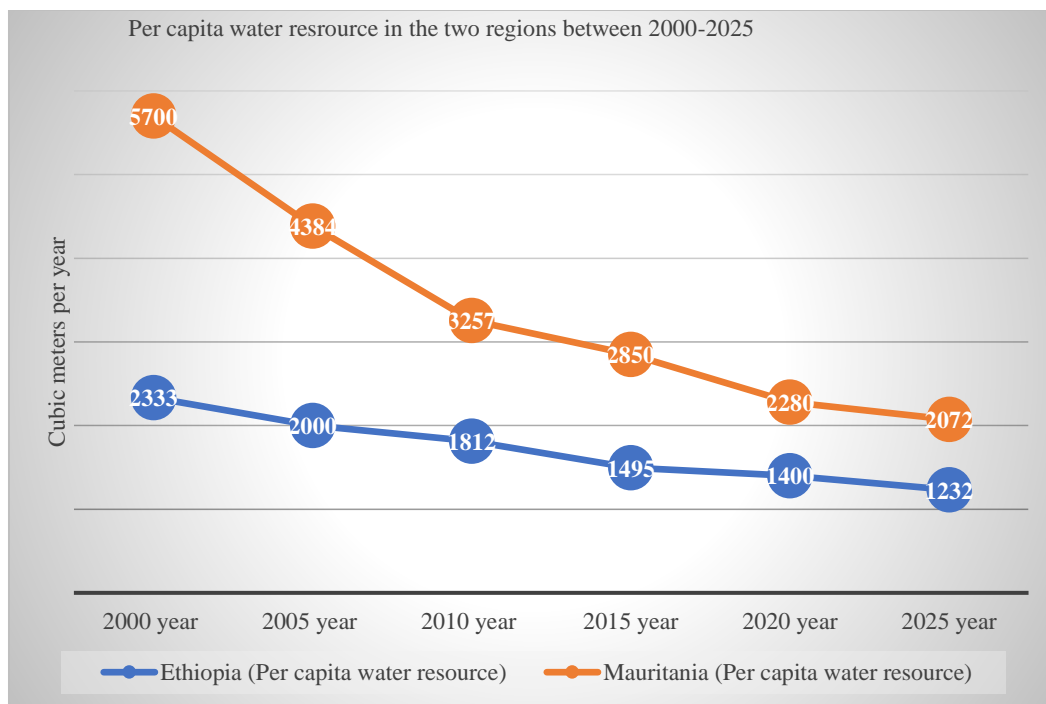


Figure 3. Water resource per capita in the two regions (m³/person/year) [29,34,35]

Figure 3 shows that although Mauritania is a water-poor country in terms of availability, the country yet consumes significant water per capita taking into account its small inhabitants. Although Ethiopia has relatively abundant freshwater availability, rapid population growth effectively resulting in the country's per capita water potential to sharply decrease notably in the past two decades.

On the other hand, Mauritania heavily relies on the Senegal River, its tributaries, and dam reservoirs, an arch dam on the Gorgol River near Fom Gleita in the Golgol region of the country. Based on total water withdrawal (Figure 3) in 2000, the country ranked among the largest water consumption with more than 5000m³ per capita [32,35]. However, given they have very significant external water dependency, its population may still remain in an insecure water condition. Additionally, given the ratio of water withdrawal to water availability exceeds 40%; the country may be categorized as high stress in a short time and extremely high stress on the year 2025 [28, 29].

The challenge of sustainably managing water systems in Sub-Saharan Africa is highly complex and multifaceted, with key obstacles including the lack of robust mechanisms for sustainable resource utilization and infrastructure management. Both regions of SSA exhibit a deficiency in long-term planning that addresses current infrastructure management challenges while promoting social and economic development and ensuring the sustainability of water resources. Wilderer [36] have demonstrated that sustainability in water resources is achieved when water abstraction rates do not surpass natural or artificial recharge rates. Similarly, Loucks and Van Beek [37] underscores the importance of considering future and long-term objectives in water resources management, alongside immediate needs. Sustainability in water resources, therefore,

encompasses the planning and management of water systems to ensure availability, accessibility, quality, security, and affordability of water amidst social, environmental, and economic challenges. This is especially difficult for economically less-developed SSA region of Ethiopia and Mauritania. Table 1 describes a summary of comparable information about the water resources potential, country area, population, land use, differences in geographic or elevation in both countries.

Table 1. Summary of water resources potential, availability and hydrographic in both the region [16, 18, 27, 42]

Country/region	Water resources potential	Country area/elevation	Population	Land use	Geographic/hydrographic
Ethiopia	<ul style="list-style-type: none"> ○ Relatively have abundant water resources (rivers, lakes and wetlands) ○ Annual rainfall varies widely across regions, with some areas receiving up to 2,000 mm per year. 	<ul style="list-style-type: none"> ○ Covers 1,112 million km² ○ Diverse topography, with elevations ranging from below sea level to over 4,500 meters above sea level 	<ul style="list-style-type: none"> ○ As of 2024 estimated to be about 132 million (Density 92.7/km²) 	<ul style="list-style-type: none"> ○ Agriculture is the dominant land use ○ Forests, grasslands, and wetlands cover significant portions of the country 	<ul style="list-style-type: none"> ○ Sub-Saharan Africa (Horn of Africa) ○ Predominantly tropical monsoon climate, with wide topographic-induced variation
Mauritania	<ul style="list-style-type: none"> ○ Significant water insecurity, the near-absolute reliance on ground waters and transboundary waters ○ Annual rainfall is very low, often less than 100 mm per year 	<ul style="list-style-type: none"> ○ Covers 1,031 million km² ○ Generally flat, with vast desert plains (highest point stands at 915 meters above sea level) 	<ul style="list-style-type: none"> ○ As of 2024 estimated to be 4,5 million (Density 3.4/km²) 	<ul style="list-style-type: none"> ○ Pastoralism and nomadic herding are common land uses, with livestock being a significant part of the economy. 	<ul style="list-style-type: none"> ○ Sub-Saharan Africa (western region of the continent of Africa) ○ Arid and semi-arid climate (desert landscapes dominate much of the country)

3.2 Water resources policies and regulations

The water resources policies and regulations may vary across countries and regions, but there are some common elements and principles (Figure 4) that set water usage and quality standards [39,40]. It points out necessary arrangements considering human and environmental needs for various water uses such as agriculture, domestic, industry, power production, and preservation of the environment and the ecology of ecosystems. As pointed out by [41], an assessment of water resources policies and regulations in Mauritania reveals challenges in ensuring robust policies and regulations, as well as a general lack of water availability and sanitation services. In Ethiopia, the rapid population growth and increased water demand are identified as

significant factors exerting substantial pressure on the sustainability of water resource management and progress toward achieving the SDGs [42,43].

Therefore, the region must remain committed to developing additional strategies and practical applications such as utilizing non-conventional water sources, promoting water reuse, and enhancing water efficiency, to support and modernize regulations for the utilization and sustainable management of water resources through the construction of multifunctional water infrastructure.

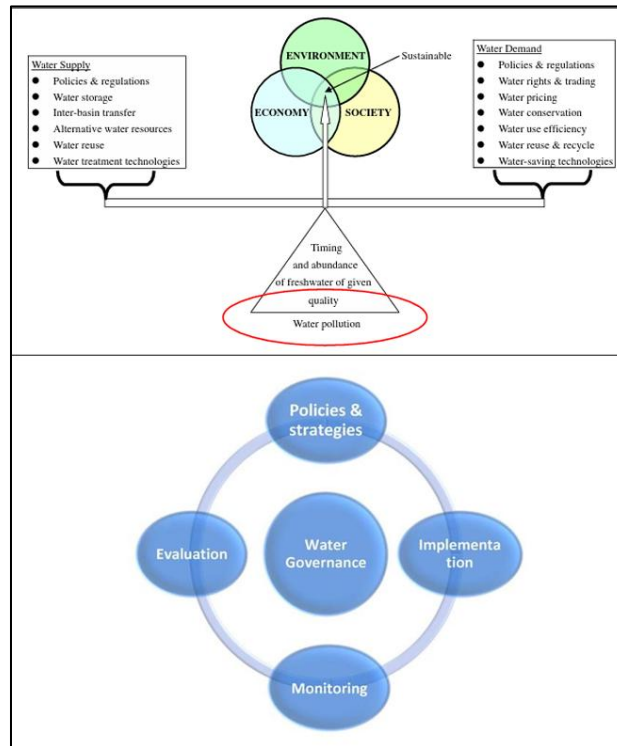


Figure 4. Schematic illustrations for sustainable water resources management and governance [39]

Water policy changes and reforms (Table 2) in Ethiopia, have been driven by the need to address water scarcity, promote sustainable water management, and enhance water security. Some notable water policy changes and reforms in the region are summarized in the following table.

Table 2. Water policy changes and reforms in Ethiopia [16]

Period	Title	Features
1997	Environmental Policy of Ethiopia	Determines water related national policy issues
1999	Water Resources Management Policy (EWRMP)	Leads water management and outline national goals for basins
2001	Water Sector Strategy	Guideline transboundary water management nationwide
2005	Water Resources Management Regulations	Determines the rights and obligations of water users

2007	Authorities Proclamation	Specify the framework of water basins and determine powers, responsibilities of the entities
2018	Powers and Duties of the Executive Organs Proclamation	Remark institutional structures and obligations for concerned authorities mainly basins authority

These policy changes and reforms in water management in Ethiopia aims to demonstrate a commitment to addressing water challenges, promoting sustainable water use, and enhancing water security. However, effective implementation and continuous monitoring and evaluation are essential to ensuring the success and impact of these reforms in achieving sustainable water management goals.

Mauritania has enacted legislative measures to define water rights and regulate water use, while also promoting community engagement and traditional practices [18]. The country's heavy reliance on groundwater underscores the critical need to prevent over-extraction and depletion of aquifers. This necessitates the implementation of clear legislative frameworks for sustainable groundwater management. Likewise, as shown in table 3, describes various ministries and institutions mandated for the leadership of governance system related to water resources management in Ethiopia and Mauritania.

Table 3. Water resources management institutions and their mandates [16, 23]

Region	Ministries and Entities	Scope, Mandate and Major Duties
Ethiopia	Ministry of Water and Energy (MoWE)	Responsible for designing water policies and legal frameworks as well as overall management of water resources
	Ministry of Irrigation and Lowland (MILL)	Mandated for the development and management of lowland areas and irrigation schemes
	Ministry of Environment, Forest, and Climate Change (MEFCC)	Conduct Research Program on Environment, water and forest Develop environmental policies and regulations to ensure ecological integrity
	Water Development Commission	Provision of water and sanitation services
	Ministry of Agriculture (MoA)	Monitor optimum utilization of water for small-medium irrigation to promote food security
	Ministry of Industry (MoI)	Ensure environmental welfare and carry out pollution control studies, in accordance with state laws and regulations.
	Regional Water Bureaus (RWB)	Administer and supervise regional water utility
Mauritania	The Ministry of Waterworks and Sanitation (MHA)	Responsible for water policy, management, as well as water supply and sanitation services -supervises locally operating companies in the water sector
	National Water Corporation (SNDE)	Responsible for urban water supply

	National Rural Water Agency (ONSER4)	Responsible for rural water supply
	the National Water Resources Center (CNRE)	Lead in charge of water resource planning and monitoring
	the National Drilling Corporation (SNFP)	Responsible for borehole drilling
	the National Sanitation Agency (ONAS)	Responsible for urban sanitation

Table 3 provides an overview of the water resource management institutions and their mandates in Ethiopia and Mauritania, highlighting the structural and institutional differences between the two countries. In Ethiopia, water resource management is distributed across multiple ministries and commissions, each with a specialized focus. For instance, the Ministry of Water and Energy (MoWE) oversees overall water policies and resource management, while the Ministry of Irrigation and Lowland Development (MILL) focuses on irrigation and lowland areas. This decentralized approach enables Ethiopia to address specific challenges, such as small- and medium-scale irrigation needs (led by the Ministry of Agriculture) and pollution control (handled by the Ministry of Industry). However, this fragmentation can also create challenges in coordination and resource allocation, which might result in inefficiencies and overlapping mandates.

In contrast, Mauritania adopts a more centralized structure, with fewer institutions handling broader responsibilities. The Ministry of Waterworks and Sanitation (MHA) plays a dominant role in water policy and management, alongside a few specialized agencies such as the National Water Corporation (SNDE) for urban water supply and the National Rural Water Agency (ONSER4) for rural areas. While this streamlined approach allows for a more unified framework, it may limit the ability to address diverse and localized water management issues comprehensively. Notably, the National Water Resources Center (CNRE) plays a critical role in resource planning and monitoring, which is essential for a country facing significant water scarcity challenges.

Overall, the table highlights the importance of tailoring water resource management structures to a country's specific needs and challenges. Ethiopia's approach may be better suited to a larger, more diverse country with varying geographical and water-related challenges, whereas Mauritania's centralized system may align with its smaller scale and simpler administrative requirements. However, both countries can benefit from improving inter-agency collaboration and aligning their mandates to avoid redundancies and ensure sustainable water resource governance. These insights are critical for understanding the institutional challenges and opportunities in water management within Sub-Saharan Africa.

3.3. Emerging water management problems and subsequent implications in the two regions

3.3.1 Water pollution

As a developing region of SSA, Ethiopia and Mauritania experiencing serious water pollution and water stress which undermine human and ecosystem functionality. Caused by the absence

of adequate infrastructure, water treatment facilities and regulations, diffuse sources of pollution and sewage discharge into waterbodies are a common practice in both the countries. The significant amount of pollution originates from various sources, including sewage and improper wastewater disposal, agricultural runoff containing fertilizers and pesticides, industrial processes, and solid waste. Regarding water quality, approximately 80% of industrial waste is released into the environment worldwide without treatment, and nearly all major rivers in Africa are considered polluted [44,45]. This pollution has a detrimental impact on water systems, human health, and the health of other ecosystems.

For example, it is concerning that, after nearly a century, cholera has reemerged in Africa, accounting for 94% of the global cholera cases reported during this time. Besides cholera, the most widespread outbreaks of waterborne diseases like typhoid fever, viruses, rotaviruses, and the parasitic protozoan are frequently linked to inadequate water supply and poor hygiene. According to reports from the WHO [46,47,48], nine out of ten cases affect children, and 50% of childhood deaths occur in sub-Saharan Africa. Furthermore, due to a significant portion of the population lacking access to sanitation and safe drinking water, the overall economic loss is estimated to be around 5% of the gross domestic product (GDP).

3.3.2 Climate change

In this twenty first century, the challenges brought on by complex natural disasters and anthropogenic dimensions hinder the ability to cope with water security issues. Climate change is a formidable challenge affecting development, particularly in Sub-Saharan Africa. It directly affects water resources through changing the quantity, variability, timing, form, and intensity of precipitation, and indirectly impacts water resources by escalating water temperature, raising evapotranspiration rate, and reducing water quality [49,50]. As illustrated in figure 5, because of the major implications of climate change and anthropogenic activities on water, food security, and socio-economic development, there would be substantial reduction in freshwater resources and agricultural production.

Approximately one-third of Africa is comprised of subtropical deserts, and the region's biomass burning contributes around 14% of global greenhouse gas emissions (CO₂ equivalent to about 1.4×10^{12} kg/year) [30]. This significantly impacts the radiation reaching the Earth, contributing to global warming. Notably, warming trends of +0.05 °C per year are observed in the highlands of East Africa, Southern Africa, and across the Sahara Desert [30]. Furthermore, according to Misra [51], by 2050, rainfall in Sub-Saharan Africa could decrease by 10%, leading to a 17% reduction in drainage, thus resulting in critical water and food insecurity. Therefore, there is a pressing need for insightful solutions to adapt to and mitigate its impacts to ensure the sustainable efficiency of finite resources. Strengthening mitigation techniques, improving adaptability, and developing nature-based solutions are essential steps to take.

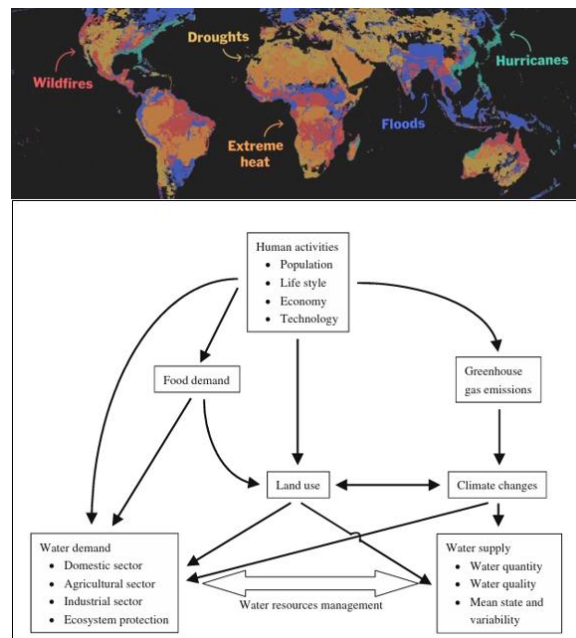


Figure 5. The evolution of natural hazards, anthropogenic activities, climate change, and water supply and demand [39]

Figure 5 effectively captures the systemic connections between environmental and human factors affecting water resources. The figure illustrates the complex interplay between natural hazards (e.g., droughts, floods, extreme heat, hurricanes), anthropogenic activities, climate change, and water resource management. It highlights how human activities such as population growth, economic activities, and technological advancements drive water and food demand, and land use changes. These, in turn, impact water demand across sectors (domestic, agricultural, industrial) and influence ecosystem protection efforts. The diagram also emphasizes the feedback loops, where climate change, driven by greenhouse gas emissions, alters water supply quality and availability, which necessitates adaptive water resource management.

3.3.3 Water demand-supply disproportionality

Water supply has been an integral part of social organization and the structural dynamics of human societies [45]. However, the disproportion between demand and supply in developing countries of SSA, especially in populous region, Ethiopia and the physically scarce region of Mauritania, will lead to unpredictable challenges over time. When the demand for water exceeds the available supply, or when its quality restricts its usability for specific purposes, water scarcity may occur [53,54]. In turn this can be driven by natural causes, such as prolonged droughts, or human-induced factors, including over-extraction, inefficient water use, and population growth. Similarly, water scarcity typically can be categorized as physical water scarcity (a shortage due to natural hydrological limits) and economic water scarcity (a lack of access due to insufficient infrastructure or investment) [55]. On the other hand, water stress describes the extent to which water demands outstrips supply in a given area, considering both

quantity and quality [56,57]. It provides a broader measure than scarcity, taking into account the availability of renewable freshwater resources, water withdrawals for agriculture, industry, and domestic use, and ecological needs. Regions experiencing water stress may have sufficient water resources in absolute terms but face challenges due to overuse, pollution, or seasonal variability.

On the other hand, water demand is influenced by several factors, including access, potential cost, socio-economic status, population, weather conditions, and water policies [58]. As such, with increased population growth, agricultural expansion, land use change, climate change, inefficient water management, and unsustainable water consumption practices, the demand for water exceeds the available supply in these two regions. This increase in demand and decrease in the supply of freshwater will put additional stress on regional countries that are already facing difficult water resource challenges. Therefore, there is a growing necessity to ensure proportionality and resilience in water infrastructure planning and management.

Water supply provision in Ethiopia is determined by various factors, primarily technical and financial, and facilities vary between urban and rural areas. The situation is dire in rural and semi-arid regions of the country, where accessing available water is challenging and boreholes can be up to 500 m deep, with the water being very hot. On the other hand, there is also a significant disparity between where most people live and where water is plentiful and easily accessible. For instance, more than 80% of Ethiopia's principal water resources are found only in the four major river basins, which contain no more than one-third of the country's population [16]. Conversely, Mauritania is arid, and its very limited freshwater resources are augmented by large rivers flowing from much wetter areas upstream of the Senegal river basin.

According to the WHO, the average water for household/domestic use per person per day to meet basic human needs should be in the range of 50–100 liters [59]. However, the average domestic water use in Ethiopia is approximately 20 liters per person per day, and in Mauritania, it is around 35 liters per person per day [60]. In Ethiopia, this lack of access is mostly due to economic and technical rather than physical scarcity, while in Mauritania, it stems from both economic and technical issues, as well as physical scarcity due to vast arid plains. Nonetheless, while it is important to better understand water demand patterns, it is essential to introduce incentives and sustainable approaches, develop context-specific financial policies, and implement alternative measures such as wastewater treatment, all tailored to the needs of the region.

3.3.4 Transboundary water issues

Roughly 40% of the global population resides within river and lake basins that span multiple countries, encompassing approximately 60% of the world's freshwater resources [61].

Transboundary water resources are especially important in Africa, where 63 international transboundary river basins cover about 62% of the region's land area and account for 90% of the total surface water [62]. They have the potential to stimulate economic growth, secure livelihoods, and alleviate poverty in Sub-Saharan Africa. However, they also pose significant challenges for cooperation, management, and governance. Additionally, many transboundary water agreements in Africa are outdated, incomplete, or poorly implemented. As a result, substantial challenges and limitations arising between upstream and downstream riparian

nations. This can impact downstream countries, furthermore, leading to concerns about water availability, quality, and ecological effects.

For example, the transboundary water resources of the Nile River basin (Figure 6) are of paramount importance to Ethiopia and the Horn of Africa, being shared among as many as 11 countries [29,63]. On the other hand, the allocation of these resources carries with it the potential for geopolitical tensions and even violent conflict within and between upstream and downstream countries.

In another part of the continent, the Senegal River (Figure 6) serves as a model for transboundary basin water management, shared among Mali, Mauritania, Senegal, and Guinea. Originating in the high plateaus of Guinea, the river traverses 1,800 km across Mali and Mauritania before emptying into the Atlantic Ocean at Saint Louis in Senegal [64,65]. The improved cross-boundary water resource management in this basin exemplifies the equitable sharing of water resources through development and management among the co-basin states of a transboundary river. However, there is a concern that significant ecological changes in the river basin may lead to decreased flow, changing habitats, and alterations in the water table of the stream aquifer, necessitating sustainable management practices.



a)

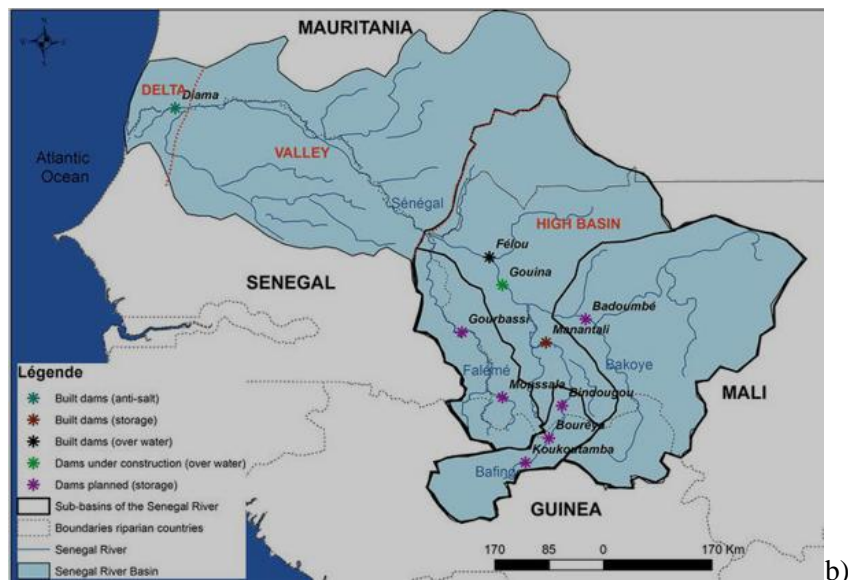


Figure 6. The Nile River (a) and The Senegal River Basin (b) [37,41]

3.3.5 Policy and institutional deficit challenge

Policy and institutional deficit are significant challenges faced by many countries in developing world [66]. Meanwhile, countries in SSA, particularly such as Ethiopia and Mauritania face significant challenges related to policy and institutional deficits that impede economic development and the sustainable management of their resources.

The region has been largely criticized for its weak institutional framework and insufficient financial resources needed to promote the sustainable socioeconomic transformation of its natural capital. Reports indicate that the two regions failed to achieve most of the Millennium Development Goals and have been performing poorly on the 2030 SDGs agenda [67,68]. Figure 7 summarizes gaps, challenges and limitations in both regions.

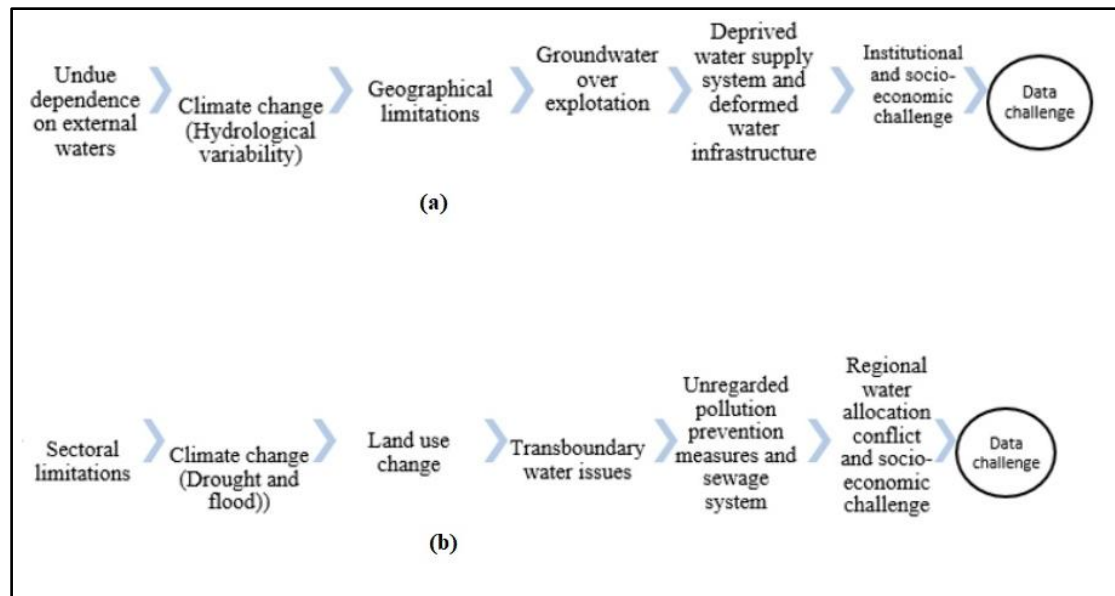


Figure 7. (a) Gaps, challenges and limitations in Mauritania; (b) Gaps, challenges and limitations in Ethiopia

The provided visualizations (Figure 7 and table 4) provide an insightful comparative analysis of water resource challenges and management strategies in Ethiopia and Mauritania.

The figure highlights the distinct, yet interconnected challenges faced by each country, while the table outlines their respective water availability, vulnerabilities, policy frameworks, governance structures, actions and outlooks. The diagram underscores the complexity of water resource issues in both Ethiopia and Mauritania. Ethiopia faces challenges such as climate variability, transboundary water issues and infrastructure gaps. Conversely, Mauritania struggles with limited water availability, heavy reliance on groundwater and rainfall, and high vulnerability to arid conditions [69,70]. Both countries face socio-economic challenges compounded by inadequate data availability, which hinders effective water resource management. While Ethiopia grapples with managing abundant but unevenly distributed water resources, Mauritania's reliance on small-scale systems and upstream transboundary waters highlights its vulnerability to external factors.

Table 4. Key aspects and water management practices in the two regions [16,33,34]

Aspects	Ethiopia	Mauritania
Water Availability	-Abundant water resources, including major rivers like the Blue Nile, but uneven distribution.	-Limited surface water; heavily reliant on groundwater and rainfall, which are highly variable.
Vulnerability	- Seasonal variability and droughts. - Over-dependence on agriculture. -Infrastructure gaps. - Transboundary water issues - Increasing challenges from climate change, including drought and reduced river flows.	-High water scarcity and arid conditions. - Vulnerable to climate impacts, such as desertification and prolonged droughts. - Dependency on small-scale agricultural water systems

		<ul style="list-style-type: none"> - Limited water supply infrastructure. - High reliance on transboundary waters and sensitive to upstream development.
Sectoral Provision	-Predominantly over 85% of water use is allocated for the agricultural sector, often inefficient due to limited technical and institutional capacity and outdated methods.	-Predominantly linked to small-scale farming and pastoralist activities, constrained by resource availability.
Water Policy Framework	<ul style="list-style-type: none"> - Environmental Policy of Ethiopia (1997). - Water Resources Management Policy (1999). - Powers and Duties of the Executive Organs Proclamation (2018). 	<ul style="list-style-type: none"> - Code of Water (2005). - Strategic Water Supply and Sanitation Plan (2011). - Integration of water policy into national drought mitigation strategies.
Governance Structure	-Partly decentralized governance with regional and basin authorities managing water resources.	-Centralized governance, with a strong focus on strategic drought response and urban water supply.
Infrastructure Development	-Significant investments in dam projects like the Grand Ethiopian Renaissance Dam (GERD).	-Limited investment in large-scale infrastructure; focus on small-scale water access points.
International Cooperation	-Active in transboundary water negotiations (e.g., Nile Basin Initiative).	- Regional cooperation for transboundary waters (e.g., established Senegal River basin development organization (OMVS) initiative.
Mitigations and Future Priorities	<ul style="list-style-type: none"> -Establishing local and regional water security council that monitor and regulate the transboundary water issues -Improving water-use efficiency. -Developing infrastructures and appraising sectoral utilizations 	<ul style="list-style-type: none"> -Enhancing infrastructures and water access in rural and urban areas. - Addressing water scarcity through sustainable practices. - Strengthening regional cooperation and climate resilience.

This analysis highlights the critical role of tailored, region-specific strategies for sustainable water management. Ethiopia’s investments in large-scale infrastructure reflect its ambition to leverage abundant water resources for economic growth, while Mauritania's emphasis on localized solutions and international cooperation addresses its acute scarcity issues. Both nations must enhance data collection and monitoring systems to enable evidence-based decision-making and foster regional collaboration to manage shared resources effectively. These findings underscore the importance of integrating socio-economic and environmental considerations in water policy to ensure equitable access and sustainability. In summary, to address these challenges and limitations, the following measures and considerations are necessary:

- Developing alternative water sources: Exploring and utilizing alternative water sources like rainwater harvesting, and wastewater recycling can help supplement sources in the region

- Developing and implementing and sustainable WASH services: This encompasses developing and implementing policies and strategies that promote the best practices and tools such as utilizing non-conventional water sources, promoting water reuse, and enhancing water efficiency, implementing water-efficient irrigation methods, rainwater harvesting, water-saving technologies, raising awareness about responsible water usage can help to achieve water security goals.
- Development of modern and environmentally sound water frameworks. So that it facilitates and coordinates the cooperation and collaboration among different competing users and stakeholders.
- Managing transboundary water resources and enhancing the capacity and awareness of transboundary water actors: Managing transboundary water resources aligns with the Sustainable Development Goals, particularly Goal 6 (Clean Water and Sanitation) and Goal 13 (Climate Action). Successful management of transboundary water resources requires diplomacy, collaboration, and trust-building among riparian countries. Cooperation and effective management of these shared water resources are vital for promoting regional stability, economic development, and environmental sustainability.
- Establishing institutional and legal frameworks and agreements: developing and implementing policies and strategies. This involves reviewing and revising existing transboundary water agreements to incorporate climate change adaptation and mitigation measures, such as water conservation, water harvesting, water quality monitoring, flood and drought management, and ecosystem restoration.

3.4 Insights from other regions of the world

Water management challenges are not unique to Sub-Saharan Africa; they are also prevalent in other developing regions, such as Latin America and Asia, where social, economic, and environmental factors create intricate barriers to sustainable water management. In Latin America, for instance, countries like Bolivia, Ecuador and Peru face water access inequities exacerbated by population growth, urbanization, and the exploitation of water resources by industries such as mining and agriculture [71,72,73]. Similarly, Asia's densely populated nations, such as India, China and Bangladesh, grapple with pollution, seasonal variability, transboundary water issues, and the overexploitation of water resources to meet the demands of agricultural and urban expansion [74]. Both regions demonstrate that while water scarcity often originates from natural factors such as drought, it is the institutional and policy gaps that exacerbate the crisis, mirroring the findings from Sub-Saharan Africa.

In critical comparison, water management in Sub-Saharan Africa shares some similarities with these regions, particularly in the emphasis on agricultural water use, which constitutes over 70% of water consumption in all cases (Figure 8). However, while Africa faces acute challenges related to limited infrastructure and financing, countries in Latin America and Asia often struggle with the fragmentation of water governance frameworks and inadequate enforcement of environmental regulations. For example, the reliance on community-based water management in Sub-Saharan Africa contrasts with Latin America's frequent use of centralized governance models, which, although more resource-intensive, are not necessarily more effective in ensuring equitable access. Asia's experiences with large-scale river basin projects, such as the great Himalayan basin, and the basins of the Indus and Ganges rivers [75] highlight the potential and pitfalls of extensive infrastructure investments—an approach that Sub-Saharan countries are beginning to explore but with significant financial and logistical constraints. These

global comparisons underscore the universal importance of integrated water resource management while highlighting the region-specific nuances that shape water governance challenges and solutions.

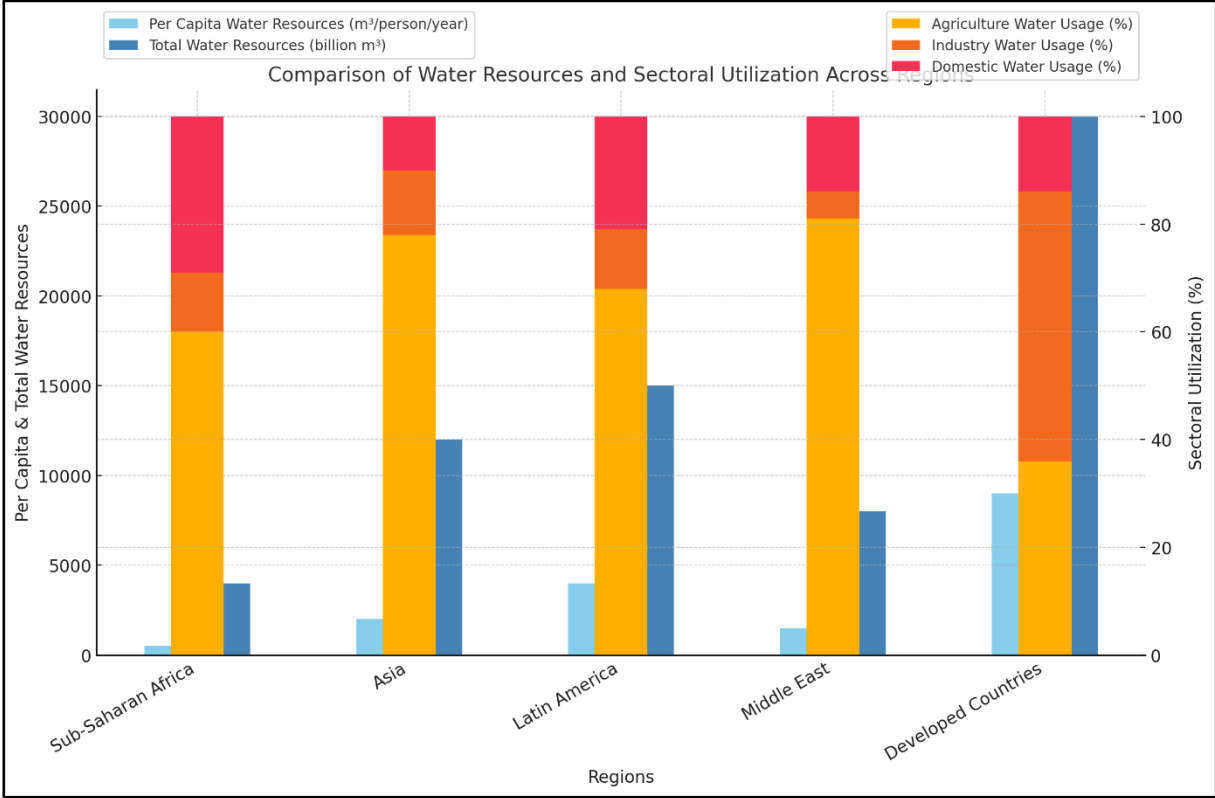


Figure 8. Worldwide water resources dimensions, sectoral and competing water uses [28,35,73]

Figure 8 illustrates comprehensive insights of water resources and competing water uses across Sub-Saharan Africa, Asia, Latin America, the Middle East, and developed countries. This broad representation underscores the disparities in water resource availability and usage patterns between different regions. For example, Sub-Saharan Africa and the Middle East exhibit relatively low per capita and total water resources compared to other regions, reflecting the chronic water scarcity issues prevalent in these areas. In contrast, developed countries and Latin America demonstrate higher water resource availability, showcasing more abundant water supplies.

On the other hand, as regards to sectoral utilization, agriculture dominates Sub-Saharan Africa, Asia, Latin America, and the Middle East, highlighting the heavy dependence on water for food production in these regions. However, in developed countries, industrial water use takes precedence, signaling a shift towards industrialization and more diversified water demands. Domestic water use remains a smaller fraction across all regions but is notably higher in developed countries due to advanced infrastructure and higher living standards. The above graph (Figure 8) effectively highlights the need for region-specific water management strategies. For instance, regions like Sub-Saharan Africa and the Middle East may prioritize

strategies to optimize agricultural water use and enhance efficiency due to limited resources, while developed nations could focus on industrial water recycling and conservation measures. Overall, the graph emphasizes the stark regional disparities in water availability and utilization, underscoring major shift in utilization and the importance of tailored, sustainable water management practices globally.

4. Conclusion

The region's water resource sufficiency and management performance lags behind the rest of the world. The water related issues in the two regions experience assorted challenges such as hydrological variability, rapid population growth, urbanization, and over abstraction. Sub-Saharan regions particularly highly populated countries such as Ethiopia and the desert climate arid countries like Mauritania endeavoring in finding sustainable solutions to water-related issues.

Ethiopia despite having tremendous potential, only a portion of this potential has been harnessed to contribute to the socio-economic development of the country meaningfully. On the other side, despite being reliance on transboundary waters, Mauritania consuming higher water withdrawal per capita and hence innovative water use practices are crucial to address water scarcity and ensure water sustainability.

The main competing uses of water in both countries within the agricultural sector require great improvement in order to ensure sustainability in water management that meets the needs of the present without compromising the ability of future generations to meet their needs. Given the rapid population growth and increasing water demand, there is an urgent need to develop stricter rules to control consumption, as well as the development of technologies that improve efficiency in this and other sectors.

In summary, addressing water management and the challenges associated with water resources in the two regions requires a collaborative and integrated approach, involving multiple stakeholders, including governments, communities, and international organizations. Moreover, it is essential to set up a water monitoring system, promote water sector financial facility, develop and implement sustainable WASH services. As a complement, the paper emphasizes revitalizing a legally binding agreement on shared water resources to increase cooperation and minimize potential water management related conflicts in the two regions.

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Formulation and characterization of steel fiber reinforced self-compacting concrete (SFRSCC) based on marble powder

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Abstract:

The main objective of this research is the formulation, and the rheological and mechanical characterization of steel fiber-reinforced self-compacting concrete (SFRSCC) based on an industrial by-product, marble powder. This study aims to develop a fiber-reinforced SCC with optimal rheological and mechanical properties. The rheological results of the SFRSCC indicate that the addition of steel fibers directly affects the workability of the mix, with this influence depending on the fiber dosage. Indeed, the introduction of fibers leads to a noticeable reduction in slump flow, along with an increase in flow time. Simultaneously, the mechanical results show a significant improvement in flexural strength and ductility as the fiber dosage percentage (%f) increases. However, the compressive strength is only slightly affected by the increase in fiber dosage. Moreover, marble powder plays a crucial role in improving the flowability and stability of the SFRSCC. It enhances the mix's compactness by filling the voids between aggregates, which promotes more homogeneous flow and reduces the risk of segregation. This synergy between steel fibers and marble powder optimizes the performance of SCC, making it suitable for various applications in the construction field.

Keywords: steel fibers, marble powder, ductility, workability, flexural strength, compressive strength.

1 Introduction

Self-compacting concrete (SCC) is regarded as a major innovation in construction materials, offering exceptional fluidity and the ability to compact without the need for mechanical vibrators. However, its mechanical performance, particularly in flexural and tensile strength, may be limited.

Jarugumalli [1] demonstrated that the addition of marble powder improves the rheological properties of SCC by up to 40%, increasing the spread diameter and reducing the flow time. However, beyond this percentage, signs of segregation were observed, while a 54% increase in compressive strength and an improvement in flexural strength were noted.

The combined effect of metallic fibers and marble powder on reinforced SCC was studied by Ahmad [2]. Adding steel fibers up to 1.5% significantly improved compressive strength (+24.8%) and tensile strength (+77.2%), while transforming a brittle failure into a ductile one. However, higher dosages reduced the workability of the concrete. Marble powder, used as a partial replacement for sand, enhanced the density and adhesion between the cementitious matrix and the fibers, facilitating the flow of the mix.

The work of M.R. Ch. Rajendra Prasad et al. [3] showed that partially replacing cement with marble powder (up to 20%), combined with 0.2% metallic fibers, significantly improved compressive, tensile, and flexural strengths, especially after 28 days. This combination also reduced cement consumption, offering a high-performance, eco-friendly concrete suitable for demanding structural applications.

Similarly, Ankathi Rajesh [4] found that substituting 15% of cement with marble powder, combined with 2% steel fibers, optimized mechanical performance while maintaining good workability. This combination improved durability while reducing the environmental impacts associated with cement production.

Wani [5] highlighted that metallic fibers influence both the rheological and mechanical properties of SCC. While fibers reduce workability, moderate dosages allow acceptable flow properties to be maintained. Mechanically, fibers increase compressive strength (+16%) and flexural strength due to their crack-bridging effect, while enhancing ductility, which is essential for structures subjected to dynamic loads.

B.C. Xavier [6] demonstrated that mixes containing 30% marble powder and 10 kg/m³ of metallic fibers achieve a specific strength 50% higher than conventional SCC while reducing cement consumption. These formulations stand out for their ecological efficiency and potential for future applications.

Vijaya Kumar [7] also observed that adding metallic fibers reduces workability but significantly improves the mechanical strength of reinforced SCC by delaying crack propagation and increasing ductility. Moreover, incorporating 15% marble powder, as demonstrated by Velci Shridevi [8], enhances compressive and flexural strengths, although workability is slightly reduced.

Haddadou N. et al. [9] studied the impact of various mineral additions and fibers in SCC, with 30% of the cement replaced by marble powder, metakaolin, or limestone powder. Marble powder improved the fluidity of the concrete, while metakaolin optimized compactness and strength. The addition of hybrid fibers (steel-polypropylene) enhanced ductility and flexural and tensile strengths while maintaining self-compacting properties in accordance with EFNARC standards, providing a sustainable solution for structural applications. In another study, Haddadou et al. [10] examined the effect of metallic fibers of various sizes. They showed that short fibers increase compressive strength by limiting microcracks, while long fibers enhance ductility and fracture energy.

Ahmad [11] employed the response surface methodology (RSM) to optimize the addition of marble waste and superplasticizers in mixes reinforced with steel fibers. While the addition of fibers improves mechanical properties up to 1.5%, higher dosages degrade rheological performance.

In another investigation, Ahmad et al. [14] analyzed the partial replacement of cement or aggregates with marble waste (WM) in SCC. Substitution up to 20% improved fluidity, compactness, and segregation resistance without compromising mechanical performance. Beyond 20%, porosity and mechanical performance decreased. This approach offers a sustainable solution by reducing waste and CO₂ emissions while maintaining good performance.

Khaloo [12] observed that increasing steel fibers improves flexural strength but reduces workability and compressive strength. Tabatabaeian [13] showed that using hybrid fibers (steel and polypropylene) reduces workability while improving flexural rigidity.

Gueciouer [15] optimized a steel fiber-reinforced SCC (SFSCC) with marble powder as an addition and partial cement replacement using design of experiments (DOE). The study showed that increasing fiber dosage enhances ductility (up to 377%) but reduces flowability. Paste volume influences strength, while fibers control ductility, validating the use of marble powder as a high-performance, sustainable material.

Finally, Keval [16], Frazão [17], and Paul [18] demonstrated that adding steel fibers significantly improves flexural, tensile, and energy absorption strengths, although excessive fiber content may reduce compressive strength.

The objective of this research is, therefore, to optimize the formulation of SCC reinforced with metallic fibers and marble powder to achieve improved rheological and mechanical properties, meeting the growing demands for durability and performance in the construction sector.

2 Experimental program

Material used

The cement used for all the compositions is a blended Portland cement (CPJ CEM II / B - 42.5). Furthermore, marble powder was used as an addition. The chemical compositions and physical properties of the cement and marble powder are provided in tables 1 and 2, respectively.

Table 1: Chemical compositions of the cement and the marble powder

Components (%)	Cement	Marble
SiO ₂	15.71	2.08
Al ₂ O ₃	4.15	0.48
Fe ₂ O ₃	2.52	0.11
CaO	60.7	54.15
MgO	2.39	0.19
K ₂ O	0.59	0.08
Na ₂ O	0.18	0.01
SO ₃	1.79	0.01
P ₂ O ₅	/	0.02
TiO ₂	/	0.01
CaO free	1.42	/
Cl	0.025	/
Ins	2.82	/
F.L	11.6	42.82

Table 2: Physical properties of the cement and the marble powder

Characteristic	Marble	Cement
Bulk specific density (g/cm ³)	0.96	/
Specific weight (g/cm ³)	2.69	2.99
Porosity	0.5	/
Color	White	Grey
Specific surface (SSB) (cm ² /g)	5910	4026
Standardized consistency H ₂ O (%)	/	26.6
Time of initial setting	/	140min
Time of final setting	/	250min

A natural silica sand (0/4) from Oued Souf and two types of crushed gravel, gravel (3/8 and 8/15), which share the same mineralogy, were used as aggregates. The main characteristics of the aggregates used are provided in table 3.

Table 3: Characteristics of aggregates

Characteristics	Symbol	Sand 0/4	Gravel 3/8	Gravel 8/15
Absolute density (g/cm ³)	P _s	2.67	2.73	2.73
Moisture content (%)	W	0.46	0.2	0
Water absorption (%)	A _s	1.68	0.45	0.30
Micro Deval (%)	M _{DE} ⁽¹⁾	/	19.98	14.72
Los Angeles (%)	L _A ⁽²⁾	/	30	41.26
Fineness modulus	M _f	2.56	/	/
Sand equivalent (%)	ESV ⁽³⁾	83	/	/
	ESP ⁽⁴⁾	81	/	/

- (1) Resistance to wear of aggregates in a rotating drum (Micro Deval test), measured according to the NF EN 1097-1 standard.
- (2) Abrasion resistance of aggregates (Los Angeles test), measured according to the NF EN 1097-2 standard.
- (3) Visual Sand Equivalent, determined by visually measuring the height of clean sand after sedimentation, without using a piston.

- (4) Piston Sand Equivalent, determined by measuring the height of clean sand after sedimentation using a piston for greater accuracy.

The superplasticizer used is a high-range water reducer (HRWR), conforming to EN 934-2, based on polycarboxylates and marketed under the name Medaflow 145. Steel fibers with hooks, referred to as 'Dramix' were used, as shown in figure 1, and their characteristics are presented in table 4.

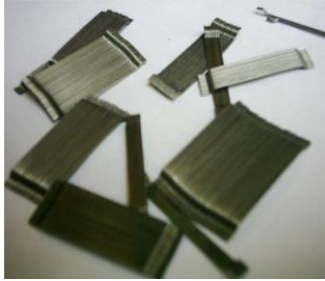


Figure 1: Steel fibers used

Table 4: Standard characteristics of fibers

Shape	Hooks
Bonding	Bonded
Length (mm)	50
Diameter (mm)	0.55
Tensile strength (N/mm ²)	1345
Aspect ratio (L/D)	55
Density	7.8

2.2 Experimental Method

To optimize the rheological and mechanical parameters of steel fiber-reinforced self-compacting concrete (SFRSCC), five (5) compositions of SCC with marble powder were produced and studied. One composition without fibers, considered as the reference (RSCC), and four others with different percentages of metallic fibers (0.2%, 0.3%, 0.4%, and 0.5%) by volume of concrete were prepared. The compositions of these five (5) SCC mixes are provided in Table 5. It should be noted that the reference concrete resulted from a prior optimization of its rheological and mechanical properties. Its optimal paste contains a cement substitution rate with marble powder of 20% (i.e., 80 kg/m³) and an additional 10% of marble powder (i.e., 40 kg/m³). The initial cement dosage is 400 kg/m³, and the specific surface area (Blaine) of the marble powder is 5910 cm²/g.

The mixes of the four (4) steel fiber-reinforced self-compacting concretes (SFRSCC) and their reference self-compacting concrete (RSCC) were subjected to standard rheological tests immediately after mixing, namely: the Abrams cone slump test, the L-box flow test, and the sieve stability test, in accordance with the recommendations of AFGC [19]. For the mechanical tests, the samples were cast and lightly vibrated to ensure a homogeneous surface. The prismatic specimens (7 × 7 × 28 cm) for the flexural tensile strength test, conducted according to the NF P18-407 standard, and cylindrical specimens (∅16 cm × 32 cm) for the uniaxial compression test, conducted according to the NF P18-406 standard, were demolded after 24 hours and cured in water at 20 ± 2 °C until the age of 28 days. Before the compression test, the cylinder faces were leveled by pouring a layer of liquid sulfur to ensure perfect flatness.

Table 5: Mix designs of the SCC studied (in Kg/m³)

	RSCC	SFRSCC1	SFRSCC2	SFRSCC3	SFRSCC4
Cement	320	320	320	320	320
Marble Powder	120	120	120	120	120
Superplasticizer	6.16	6.16	6.16	6.16	6.16
Water	176	176	176	176	176
Sand (0/4)	940	940	940	940	940
Gravel (3/8)	506	506	506	506	506
Gravel (8/15)	337	337	337	337	337
Fibers	0	15.6	23.4	31.2	39

3 Results and discussions

The conventional rheological tests conducted on the four (04) steel fiber-reinforced self-compacting concretes (SFRSCC), as well as on the control concrete, include the slump flow test using the Abrams cone, the flow time, sieve stability, and the L-box test, as illustrated in figure 2.

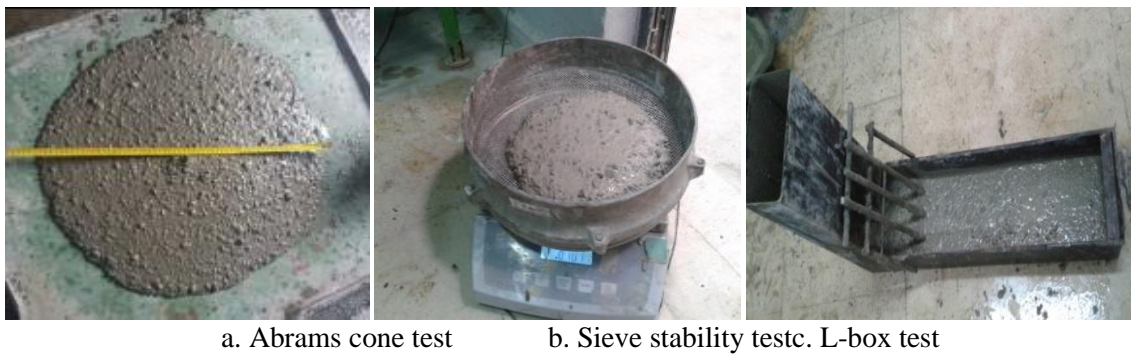


Figure 2: Fresh state tests of the studied self compacting concretes

The results of the rheological parameters of the four (04) fiber reinforced self compacting concretes (SFRSCC) studied, as well as those of the reference concrete, are represented by the histograms in figures 3, 4, 5, and 6, as well as by table 6.

Table 6: Results of the fresh-state tests of the studied self-compacting concretes

Type of SCC	Slump flow (cm)	T500 time (s)	L-box H2/H1	Sieve stability (%)	Bulk density (Kg/m ³)
RSCC	75	2.36	0.93	8.33	2367.02
SFRSCC1	70.25	2.83	0.89	3.89	2413.70
SFRSCC2	69	3.05	0.87	5.83	2401.24
SFRSCC3	67	3.61	0.84	2.08	2372.60
SFRSCC4	65.5	3.93	0.81	1.66	2360.80

The results in figure 3 show that all concretes exhibit slump flows in compliance with SCC requirements, with a uniform distribution of aggregates and fibers. The fiber-reinforced concretes with marble have a slightly reduced spread compared to the control concrete, which confirms the findings of Haddadou [20], Boulekbache [21], and Khaloo [18], who demonstrated that the addition of fibers decreases the spread of SCCs. This is also consistent with Groth's conclusions [22], which demonstrated that workability depends on the dosage and geometry of steel fibers, particularly their aspect ratio.

Figure 4 shows that the influence of fibers on the flow time (T500) is significant: the higher the fiber dosage, the higher the T500. This is explained by the overlapping of fibers, which creates blockage zones, thus delaying the flow. These observations confirm the findings of Hadaddou [20].

The results of the L-box test show that the highest filling value is achieved with the reference SCC (RSCC) and it decreases with the addition of fibers. This phenomenon, also observed by Haddadou [20], indicates that increasing the fiber content hinders the flow, leading to blockage, particularly for SCCF5. Nevertheless, all mixes exhibit filling rates that meet the AFGC [19] requirements, as illustrated in figure 5.

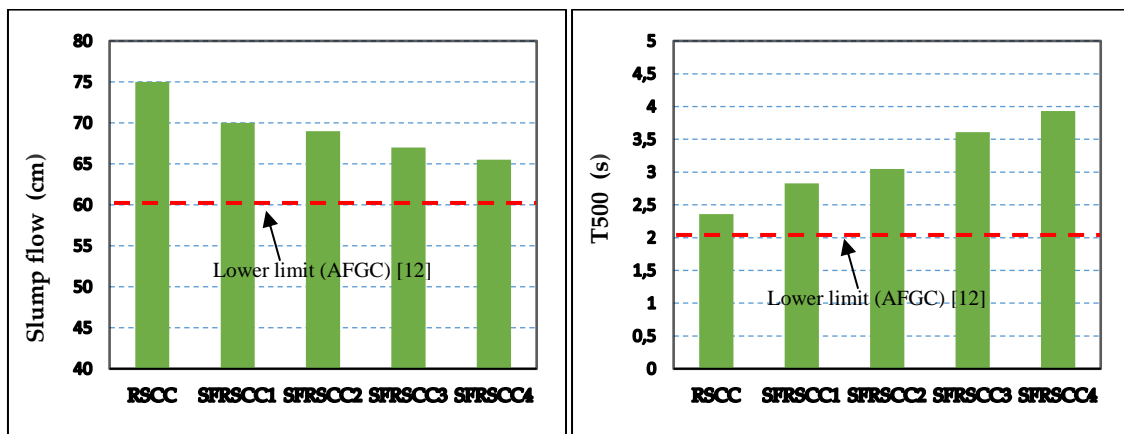


Figure 3: Slump flow values for the different self compacting concretes.

Figure 4: T500 time values for the different self compacting concretes.

The results of the sieve stability test show an improvement in stability with the addition of steel fibers. The highest value is recorded for the reference SCC, and it decreases with the incorporation of fibers, which is explained by the good adhesion between the paste and the fibers. None of the studied SCCs present a risk of static segregation, as the paste loss rate remains below 15% and meets the requirements (see Figure 6).

It should be noted that the bulk densities of the fiber-reinforced SCCs (SFRSCC) are almost identical to those of the fiber-free concrete, as the weight of the steel fibers is negligible compared to that of the aggregates. This result has also been observed in the work of Boutben [23].

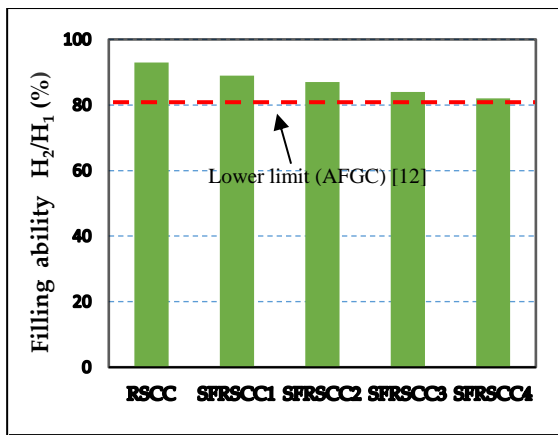


Figure 5: Variation in filling ability for the different SCCs

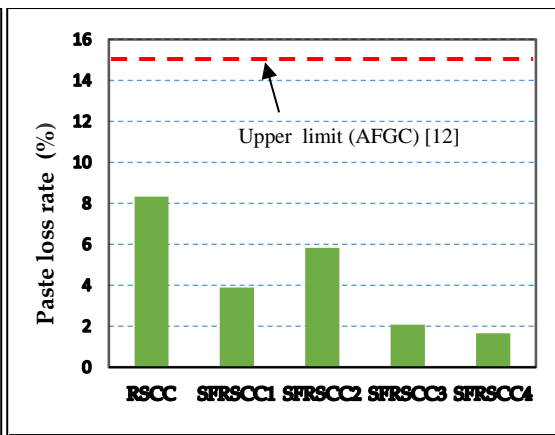


Figure 6: Variation in sieve stability for the different SCCs.

Regarding the mechanical characterization, as shown in figures 7 and 8, it is observed that after failure, the distribution of fibers is not homogeneous in the fiber-reinforced SCC specimens subjected to mechanical tests.



Figure 7: Distribution of fibers in the SCC specimens subjected to the bending test



Figure 8: Test method and specimen failure with 0.5% fiber in the case of the compression test
The results of the compressive and flexural strengths of the studied self compacting concretes are summarized in table 7.

Table 7: Results of the mechanical strengths of the studied self compacting concretes

Type of SCC	Compressive strength (MPa)	Flexural strength (MPa)
RSCC	37	5.15
SFRSCC1	38.3	5.55
SFRSCC2	39.2	5.81
SFRSCC3	40.6	6.08
SFRSCC4	41	6.34

Based on figure 9, a considerable improvement in flexural strength is observed following the introduction of fibers into the compositions of the self-compacting concretes. This figure shows that the fiber-reinforced SCC with 0.5% fibers exhibits a higher flexural strength compared to the fiber-reinforced SCC with 0.2% fibers, as well as to the control SCC.

A gain of approximately 23.10% was recorded compared to the control concrete for a fiber dosage of 0.5%. This increase is attributed to the good adhesion between the fibers and the concrete matrix. This result is often confirmed by other studies such as those by Grunewald [24], Gencel [25], Balaguru [26], and Deeb [27]. For example, it was shown by Gencel [25] that for a dosage of 30 kg/m³ of metallic fibers, the flexural strength increased by 51.7%.

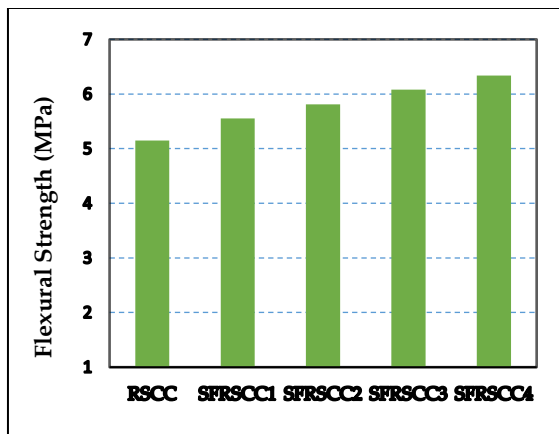


Figure 9: Variation in the flexural strength of the different self compacting concretes.

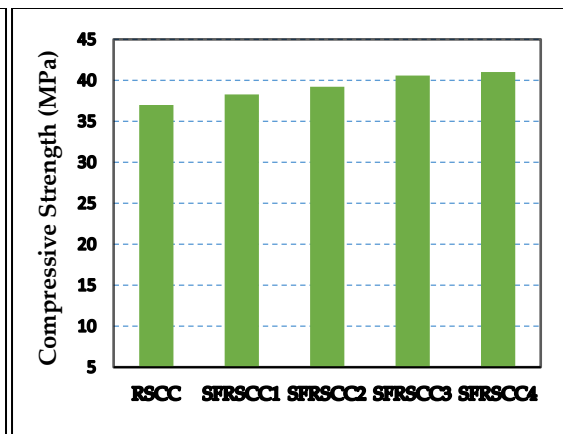


Figure 10: Variation in the compressive strength of the different self compacting concretes.

Figure 10 shows the variation in compressive strength as a function of fiber dosage. A slight increase in compressive strength of approximately 10.8% is observed compared to the control concrete for a fiber dosage of 0.5%. This result is consistent with the works of Gencil [25] and Madandoust [28], which have demonstrated that the increase in fiber dosage slightly influences compressive strength.

It should be noted that it is not only the increase in flexural strength that is aimed for, but also the ductile behavior that makes the use of fiber-reinforced concrete beneficial. Based on figures 11, 12, and 13, it can be concluded that the increase in fiber dosage improves ductility. The failure of the control concrete is brittle; when the strength limit is reached, a sudden fracture is observed. This is explained by the low tensile strength of the concrete alone under the stresses developed in the tension zone of the flexural element. This failure is illustrated in figure 11.



Figure 11: Failure of the control concrete (Brittle failure at mid-span).

For the non-fiber-reinforced concretes, the specimen is broken with a crack initiated at the lower fiber level. The crack propagates vertically upward, dividing the specimen into two parts.

According to figure 12, the failure mode observed in the fiber-reinforced specimens with 0.2%-0.3%-0.4% fibers by volume of the concrete matrix shows a significant improvement regarding the initiation of microcracks. This is explained by the presence of fibers, which serve to stitch the microcracks and hinder the rapid development of the main crack opening.



Figure 12: Ductile failure mode for SFRSCC1, SFRSCC2 and SFRSCC3.



Figure 13: Densification of cracks and ductile failure for the case of SFRSCC4 (0.5% fibers).

Under the effect of a redistribution of tensile stresses in the bending zone, the main crack is accompanied by other independent cracks with significant openings or by small secondary cracks originating from the main crack.

According to figure 13, for the fiber-reinforced self-compacting concrete specimens with 0.5% fibers by volume of the concrete, a more ductile failure is observed, characterized by the presence of a main crack of lesser thickness at the supports, as well as a densification of microcracks across the entire normal face of the flexed element. This is explained by the high fiber content in the concrete matrix.

In addition to its technical advantages, the use of marble powder as a partial replacement in the formulations of steel fiber-reinforced self-compacting concrete (SFRSCC) also offers significant environmental benefits that deserve to be discussed. The use of marble powder as a partial substitute for cement or fines in self-compacting concrete (SCC) presents notable environmental advantages. Firstly, it valorizes an industrial by-product from marble cutting and polishing, thereby reducing the amount of waste sent to landfills and limiting environmental pollution. Secondly, replacing cement with marble powder helps reduce CO₂ emissions associated with cement production, an energy-intensive process responsible for approximately 7% of global CO₂ emissions. Thirdly, by integrating a local material such as marble powder, which is particularly abundant in Algeria, the carbon footprint associated with transporting imported raw materials is reduced. Lastly, this approach promotes a circular economy by incorporating industrial by-products into innovative concrete formulations while preserving natural resources such as limestone and aggregates. These benefits contribute to making SCC more sustainable and environmentally friendly.

However, the implementation of these innovative formulations raises important questions regarding their practical feasibility, particularly in terms of costs, logistics, and large-scale adoption in real-world projects. The feasibility of steel fiber-reinforced self-compacting concrete (SFRSCC) formulations based on marble powder in Algeria appears promising but comes with certain challenges. The abundant availability of marble powder, a by-product of the local industry, provides an economic advantage by reducing raw material costs. This valorization also limits transportation expenses, as the powder is often produced near construction sites. However, the high cost of steel fibers remains a barrier, potentially hindering their large-scale adoption. In terms of logistics, the supply chain required to uniformly integrate these materials into SCC demands optimal coordination, particularly to ensure consistent powder quality. Moreover, companies must overcome resistance to adopting innovative formulations, which are often perceived as risky. Finally, awareness campaigns and real-world testing are necessary to demonstrate the performance and durability of these SFRSCC formulations, thereby facilitating their integration into local projects.

4 Conclusion

The results obtained in this study highlight the significant influence of incorporating metallic fibers and marble powder on the rheological and mechanical properties of self-compacting concrete (SCC). From a rheological perspective, the addition of marble powder notably improved the fluidity and workability of the mixes, which is essential for ensuring proper distribution of aggregates and homogeneity within the concrete matrix. However, the introduction of metallic fibers, although causing a slight decrease in cone slump, showed a positive effect on the stability of the mixes, minimizing the risk of segregation. The observed reduction in cone slump is offset by an increase in flow time and improved resistance to segregation, especially for high fiber dosages.

On the mechanical side, metallic fibers significantly enhanced flexural strength and ductility. Specifically, a 23% increase in flexural strength was observed with a fiber dosage of 0.5%, confirming their role in bridging cracks and distributing stresses. In contrast, compressive strength was only slightly affected by the addition of fibers, with a modest increase of 10.8%. This suggests that while fibers are particularly effective in improving tensile behavior and ductility, their impact on compressive strength remains limited.

The change in failure mode, from brittle to ductile behavior, illustrates the contribution of metallic fibers in controlling crack propagation after the initial microcracks appear. This shift in behavior is crucial for structural applications where energy dissipation under load is required, particularly in environments subjected to dynamic loading.

This study advances knowledge in the field by highlighting the synergy between metallic fibers and marble powder, which optimizes both the rheological and mechanical properties of self-compacting concrete (SCC), while opening up promising perspectives for the design of more durable and high-performance concrete, leveraging local materials and industrial by-products. To further explore these results, microstructural studies could be conducted to better understand the interactions between the cement matrix, metallic fibers, and marble powder, particularly regarding adhesion and microcrack propagation. A finer optimization of fiber and marble powder dosages could improve both rheology and mechanical properties simultaneously.

Moreover, testing these formulations in structural elements subjected to dynamic loads or harsh environmental conditions would validate their potential in real-world applications. The exploration of hybrid formulations combining metallic and synthetic fibers could also offer an interesting compromise between rheology and mechanical performance. Thus, the findings of this research lay the foundation for the sustainable development of fiber-reinforced self-compacting concrete (SCC), meeting the growing demands of the construction industry in terms of performance and durability.

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Optimization by RSM of reinforced concrete domes with meridian ribs, under static loading.

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Abstract

Reinforced concrete domes with meridian ribs present a suitable solution for covering large spaces, but their optimization in terms of strength and stability remains a challenge not yet mastered. This work presents a new global mathematical approach to optimizing these structures, starting with a primary configuration braced at the top and bottom with ring beams. This configuration will undergo optimization via numerical simulation to ensure its mechanical performance. The main variables studied include dome diameter, rib spacing, thickness and supported load. A Response Surface Methodology (RSM) is then used to correlate these parameters. Ultimately, a cost-oriented objective function is derived, incorporating a load-bearing capacity coefficient. This approach proves effective and can serve as a valuable tool for designers seeking to optimize their projects.

Keywords: reinforced concrete domes, meridian ribs, optimization, RSM, global approach.

1. Introduction

To cover a space, you'll need a structural system that's adequate in terms of strength and stability, with pleasing architecture and sufficient durability. Several choices can be envisaged. And to technically optimize the choice to be adopted in terms of mechanical performance, a load-bearing coefficient [1] is used to measure the capacity of such a structural system. This coefficient is the ratio between the load supported by the system and the weight of the structure. The higher the coefficient, the higher the performance of the structural system. Three-dimensional thin-walled reinforced concrete structures offer a simple, economical solution, and are widely used in civil and industrial construction. However, they share the common characteristic of being among the most delicate structures to study.

Reinforced concrete dome structures reinforced with meridian ribs are one of the main components of this range of structures. The ribs are introduced into the system to give the

structure additional rigidity against the stresses applied to it. When it comes to thin-plate roofing with meridian ribs for any structure, the designer is faced with the following two classic imperatives: Knowing how to analyze the structure in order to dimension it with sufficient safety, knowing how to design, plan and build the structure rationally and economically. But for civil engineers, in the field of thin shells, a third essential requirement arises: knowing how to choose optimal shapes. Before explaining our contribution to this work, it is important to review the little numerical and experimental research carried out on reinforced concrete domes.

In a recent article [2], experimental tests were carried out on a 60 cm diameter reinforced concrete dome model, showing the influence of the ring beam at the base of the dome on its overall mechanical behavior. This suggests the contribution of such a reinforcement at the base. Another numerical study using ANSYS [3] on reinforced concrete domes with several design variants of the structural system, shows that increasing the percentage of steel in the concrete has no significant influence on the mechanical performance of the dome. On the other hand, the presence of a meridian rib reinforcement with a ring beam at the base provides a significant reinforcement contribution. This study also reported a variation in stresses from an optimum dome diameter of 8 m.

An analytical study on reinforced concrete semi-spherical domes, in non-linearity [4], with and without meridian ribs, using SAP2000, concluded that the mechanical response of structural systems of pairs with meridian ribs is better than that of domes without meridian ribs, this finding being more pronounced at larger diameters. With regard to concrete strength class, a study of various cases of structural systems for reinforced concrete domes [5, 6], shows a minimal increase in mechanical performance when moving from a concrete class of 20 to 25 to one of 30 or 35 MPa.

Using Comsol Multiphysics, an optimization study [7] showed that the choice of optimization method significantly affects the mechanical response of domes, but is more dependent on the geometry and size of the finite elements. However, these results show that further research into optimizing the shape of these systems is possible. The initial shape of the spherical or semi-spherical dome has a considerable influence on the mechanical response of the structural system. The number of ribs has a significant influence on the dome's mechanical behavior: by going from two ribs to four, the breaking load increased by 25% [6]. It should also be noted that the spherical dome, despite its compression response, remains favorable for concrete, but the quantity of concrete is important here.

Parametric analysis is the key to optimizing a dome, a study led by Jain, Nayak, and Walke [8] presents a bibliographical synthesis of recent research on the subject in terms of analysis and design. The shape of the double-curved spherical dome with meridian ribs has been studied by N. A. Jasim et al [9], who showed that the ribs can be subject to tension, and also observed that the maximum displacement is not always located at the top. Finite element models of axisymmetric reinforced concrete domes with two rings were analyzed [10] by three software packages (Abaqus, FEAS, ARSAP). The results show a 30% difference between the analysis models, and a significant convergence between the three calculation codes. On the effect of

shape, using the ratio of height to diameter, Peter Chacko et al [11] showed that the best shape for spherical domes to resist vertical and horizontal loads is between 0.3 and 0.35.

From a fatigue point of view, a recent study by LOGZIT et al [12] showed that these systems are subject to fatigue phenomena, with a direct relationship proposed between behavior under monotonic loading and fatigue loading. The subject of improving structural systems under wind load was studied by Ife Olorun O. and Ronggui L. [13], who showed that system materials can affect the mechanical behavior of the structure. The bibliographical references cited above provide advanced optimization methods for reinforced concrete domes with meridian ribs, and can serve as a starting point for further research in this field. But careful analysis of all the studies cited above shows the absence of a global approach integrating all the parameterized data to arrive at the final optimization solution. These studies use a straightforward approach to describe only the mechanical behavior of the domes under the influence of the various optimization variables. The designer will need a mathematical formulation linking all the parameters to meet a mechanical performance or economic objective. In this work, we propose a new optimization approach, targeting an objective through parameterized analysis, by means of a mathematical formulation, giving the numerical response prediction. This model will be able to give the final solution sought, knowing the variable parameters of the study. The importance of this model is that the constraints or optimization conditions are not included in the final formulation, but are taken into account in the preliminary phases of the approach.

2 Optimization parameters

Optimization is a mathematical process aimed at finding an objective function. It is used in many fields, its objective being to obtain the ideal variant of a study by including variables and conditions. A mathematical foundation for optimization theory and its applications in science is presented in an article by G. R. Sinha [14] and the book by M. Cavazzuti [15]. An example of the application of parametric optimization concepts using the design of experiments method on reinforced concrete beams is also discussed by Raouache et al [16].

In parametric shape optimization, the shape is governed by a small number of variable parameters. These parameters generally have a physical meaning, and the model's dependence on them is therefore explicit. They can be length, thickness, radius, angle or height. During optimization, the initial shape is modified through the evolution of the parameters assumed by the model. This approach has the effect of limiting exploration of the design space, since it does not offer any variation of the shape boundary or its topology. The optimal shape found will be similar to the initial one, but with different dimensions and layouts. As a first approximation, the initial shape in this new optimization approach (Figure 1) is deduced from experimentation by analyzing all theoretical and experimental studies to arrive at an ideal initial design solution. From previous studies, we can conclude that the best configuration of the reinforced concrete structural system is in the form of a low-profile or semi-spherical dome, with an annular beam at the top, and another at the base. These two annular beams are radially braced by a well-defined number of meridian ribs. This initial solution was deemed satisfactory in terms of both mechanical and economic performance.

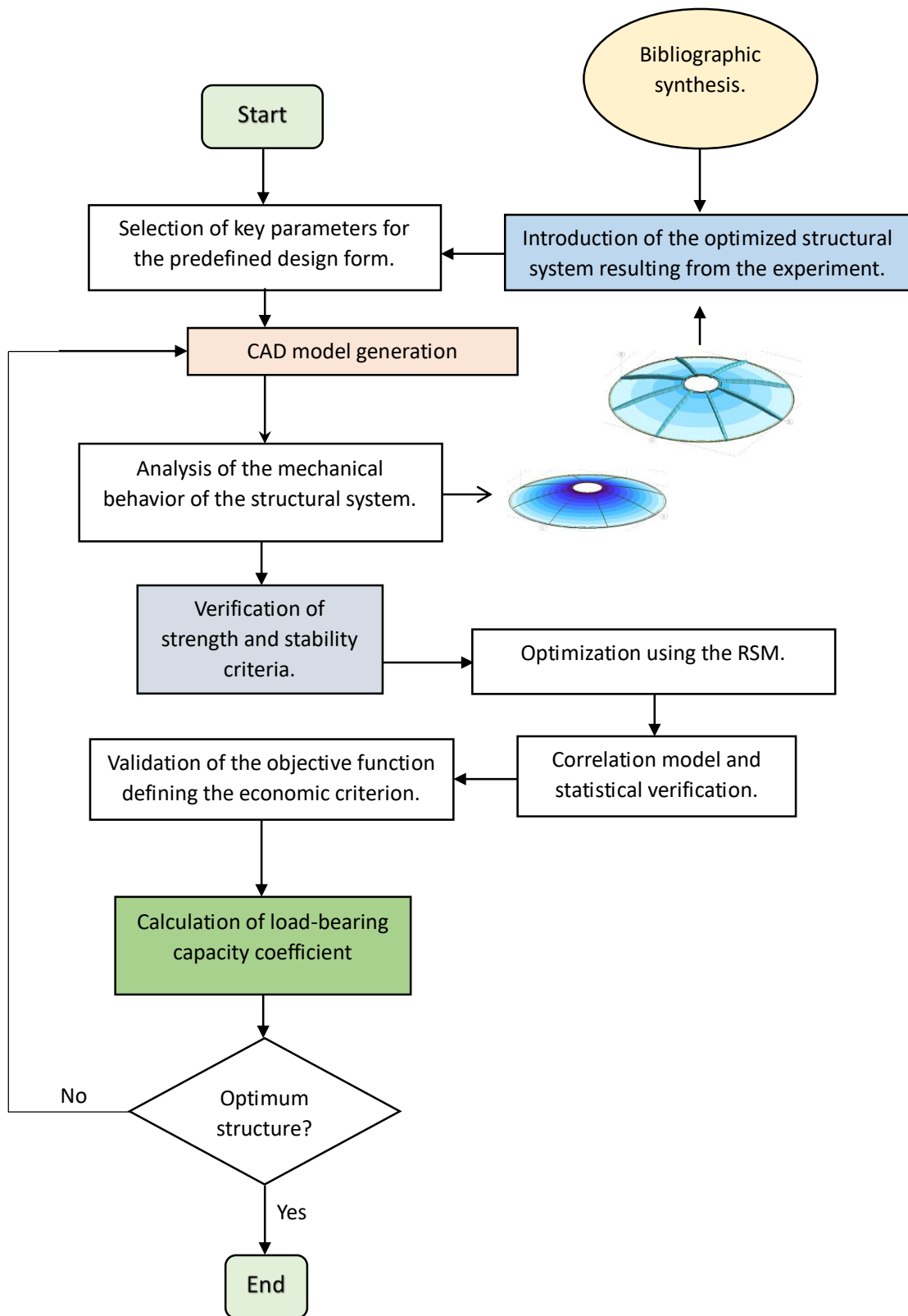


Figure 1: Global optimization approach.

This structural choice will be introduced into the optimization model in order to precede a second approximation aimed at finding the global approach relativizing the variable parameters by a global objective function.

Once the shape parameters have been chosen, an optimization procedure can be implemented. The general formulation of an optimization problem consists of three main parameters: the *objective function*, the set of admissible *variables*, and the *n* study *constraints*. Having posed the optimization problem, the next step is to adopt a strategy for solving it. Design-of-experiments and response-surface optimization are the most common approaches used in industry, shape and material design. However, this method is less widely used in structural systems optimization.

The objective function here is the ideal form and arrangement, which results in a design that meets the strength and stability requirements governed by reinforced concrete regulations [17], to which is added an economic concern representing a minimum quantity of concrete in the structure. To compare the mechanical performance of two or more configurations of the structural system, we adopt here the notion of the relative capacity coefficient of the structure [1]. As for the study variables, the design of the meridian-ribbed dome will be governed by four main parameters: dome thickness (e), distance between meridian ribs (Esp), dome diameter or span (D), and static load supported per $m^2(Q)$.

The constraints or study conditions are the structural system strength and stability criteria to be verified before validating the selected design. They involve checking the maximum stresses at dome level against those tolerated by regulations, as well as checking the maximum displacements. At the end of these verifications, we arrive at configuration i , to which we add the verification of the weight of the structures in relation to configuration $i-1$. The best solution is the one with the minimum weight. In this way, the solution found at the end of the optimization process is quite different from a simple dimensioning: it will present the best configuration of the structural system among several verifying the dimensioning aspect.

The quantity to be minimized, called the *objective function* or *cost function*, is therefore the volume of the dome and ribs "V". The dome (Fig. 1) consists of a thin shell of thickness "e", radius "R" and deflection "f", with arched ribs of cross-section "s", length "l" and number "n". In this configuration, the variables: e, R, f, s, l, and n are the set of optimization variables. In addition to the fixed diameter "D" of a given case, other *constraints* can be taken into account. Indeed, we can consider that the dome deflection f must remain within the interval $D/8$ and $D/10$ to be in the case of low-profile or semi-spherical domes. Since the optimization *variables* represent dimensions, mathematically it seems natural to choose the set of positive reals as the space of admissible *variables*. In other words, the variables (e, R, f, s, l and n) take their values in R^+ .

The variables: e, R, f, s, l , and n are the optimization *variables* that drive the shape of the dome. This classical optimization problem can be formalized mathematically by the following equation (1):

$$\begin{aligned}
 & \checkmark \text{ Minimize : } V = 2 \pi .R. f. e + (s. l. n) \\
 & \text{Such as: } (e, R, f, s, l, \text{ et } n) \in \mathbb{R}^6 \\
 & D = \text{Fixed for the specific case.} \\
 & \text{Such that: } f = \text{between } D/8 \text{ and } D/10 \\
 & \checkmark \text{ Verification of regulatory limits} \\
 & \text{and constructive provisions.}
 \end{aligned} \tag{1}$$

To obtain the objective function, the RSM will be adopted, using stepwise approximation. This method determines the best configuration of meridian ribs to maximize the structure's strength and stiffness, while minimizing the amount of material used.

3 Numerical simulation

As a first step, and using the finite element method, several study cases of meridian ribbed domes were simulated by the software. The second stage consists of numerical analysis using the design of experiments method, with the results found in the first stage subsequently being exploited to design the final numerical model. The first step is to define the initial shape based on the geometric entities derived from the CAD models. Figure 2 shows the structural system model adopted, with the required variables. A computer program derived from the strength-of-materials formulas used for dimensioning was developed in direct connection with each CAD configuration. For this section, and before moving on to the RSM, the following assumptions were made in the numerical simulation:

- ✓ Reinforced concrete domes with meridian ribs,
- ✓ Dome diameter (span) is variable,
- ✓ Dome deflection “ f ” is between $D/8$ and $D/10$.
- ✓ Concrete class 25 MPa.
- ✓ Linear elasticity analysis.
- ✓ Assume structure's own weight G .
- ✓ Uniform static load Q per m^2 on the dome of : 100 to 200 Kg/m^2 . In accordance with standards and regulations, see e.g. reference [17].
- ✓ Load weighting according to regulations: $G + Q$ and $1.35 G + 1.50 Q$.
- ✓ As a first approximation, check load-bearing capacity.

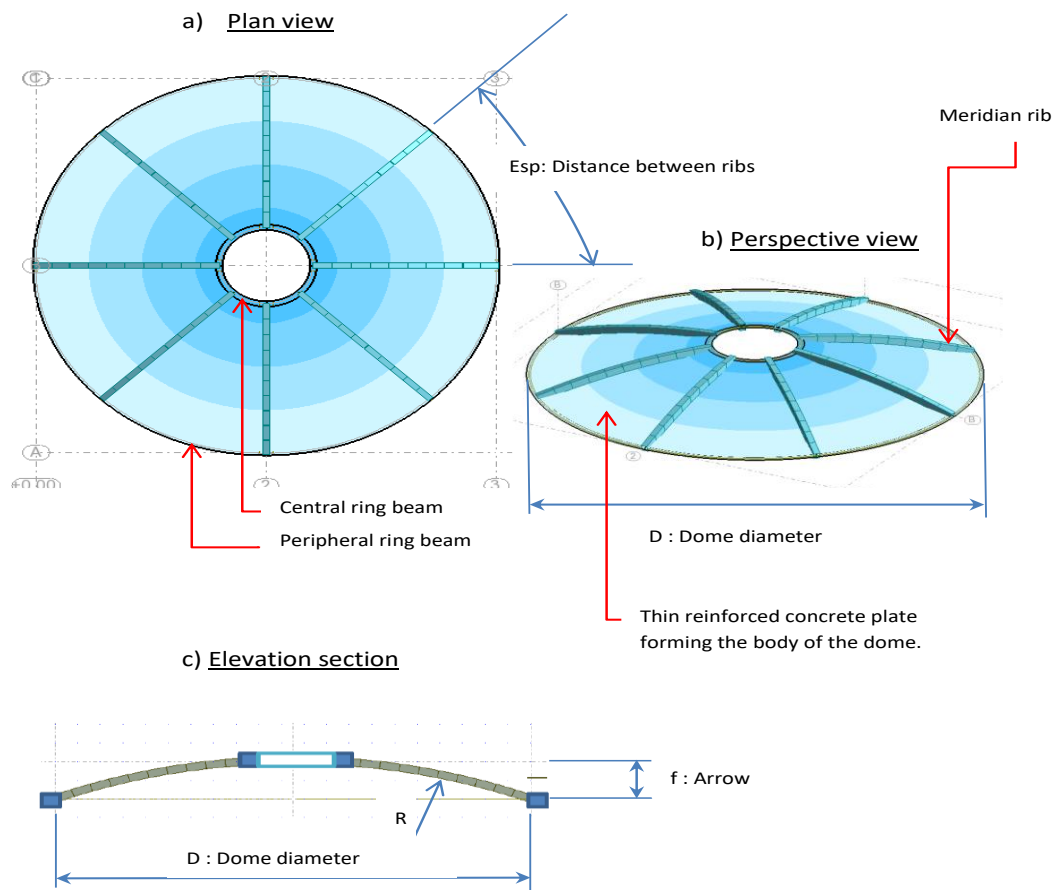
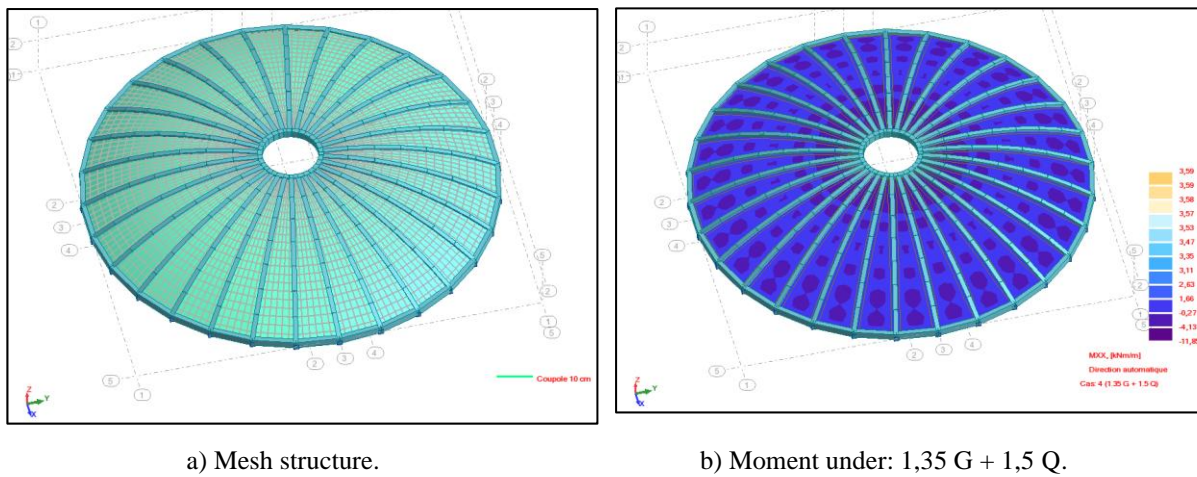


Figure 2: Geometric characteristics of the structural system adopted.

By analyzing 21 cases of domes with meridian ribs, and after verifying all the resistance and stability conditions, a graphical extract of the mechanical behavior of structural system No. 3 (see figure 4) is illustrated in figure 3.



a) Mesh structure.

b) Moment under: 1,35 G + 1,5 Q.

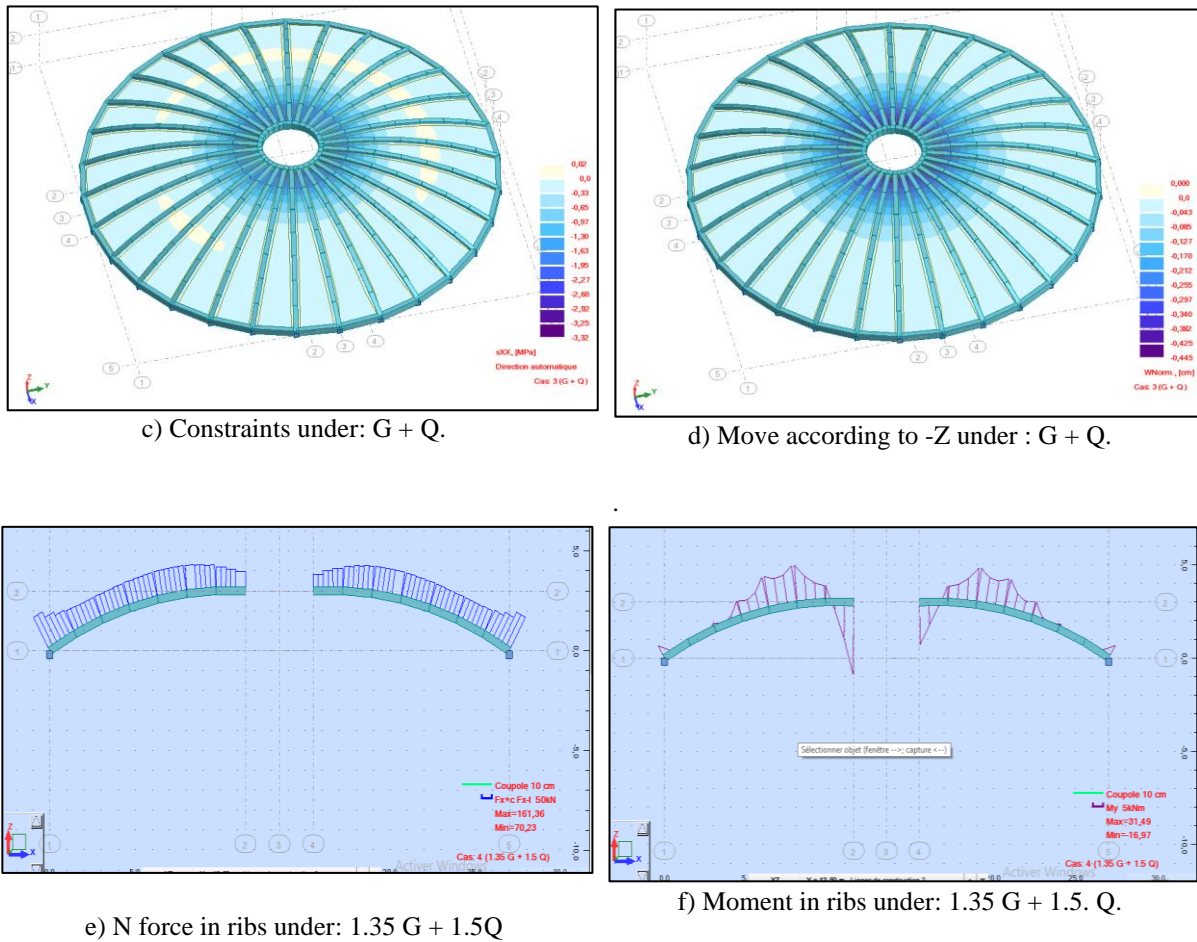


Figure 3: Mechanical behavior of the meridian-ribbed dome.
 Case N°3: $D = 27 \text{ m}$, $f = 3 \text{ m}$, $e = 10 \text{ cm}$, $E_{sp} = 3 \text{ m}$, and $Q = 200 \text{ Kg/m}^2$.

Figure 3 shows the mechanical response of the structural system under its own weight combined with an operating load of $Q = 200 \text{ Kg/m}^2$. Figure (3,a) shows the finite element mesh, which is of the 4-node quadrangle type for surface elements, and of the 4-node tetrahedral type for volume elements. The element size is set at 0.5 m max. Figure (3,b) shows the mapping of the moment in the dome under the combination $1.35 G + 1.5 Q$, the moment varies from 3.59 to 11.85 KN.m, these relatively low values show that the system is loaded more in compression than in bending. Figure (3,c) shows stress mapping at the dome under $G + Q$, with a maximum value of 3.92 MPa, still below the tolerated limit. Figure (3,d) shows the displacement map under $G + Q$, with a maximum value of 0.445 cm at the top of the dome, well below the maximum tolerated deflection ($D/200$). Figures (3,e) and (3,f) show the normal force and bending moment, respectively, in the meridian ribs, which are subjected to compound bending in places. The 21 cases studied will follow the same process of monitoring mechanical behavior, and once the structural system has been validated, it can be considered as the result of numerical simulation.

The numerical simulation results representing the matrix of experiments are shown in Fig 4 and 5.

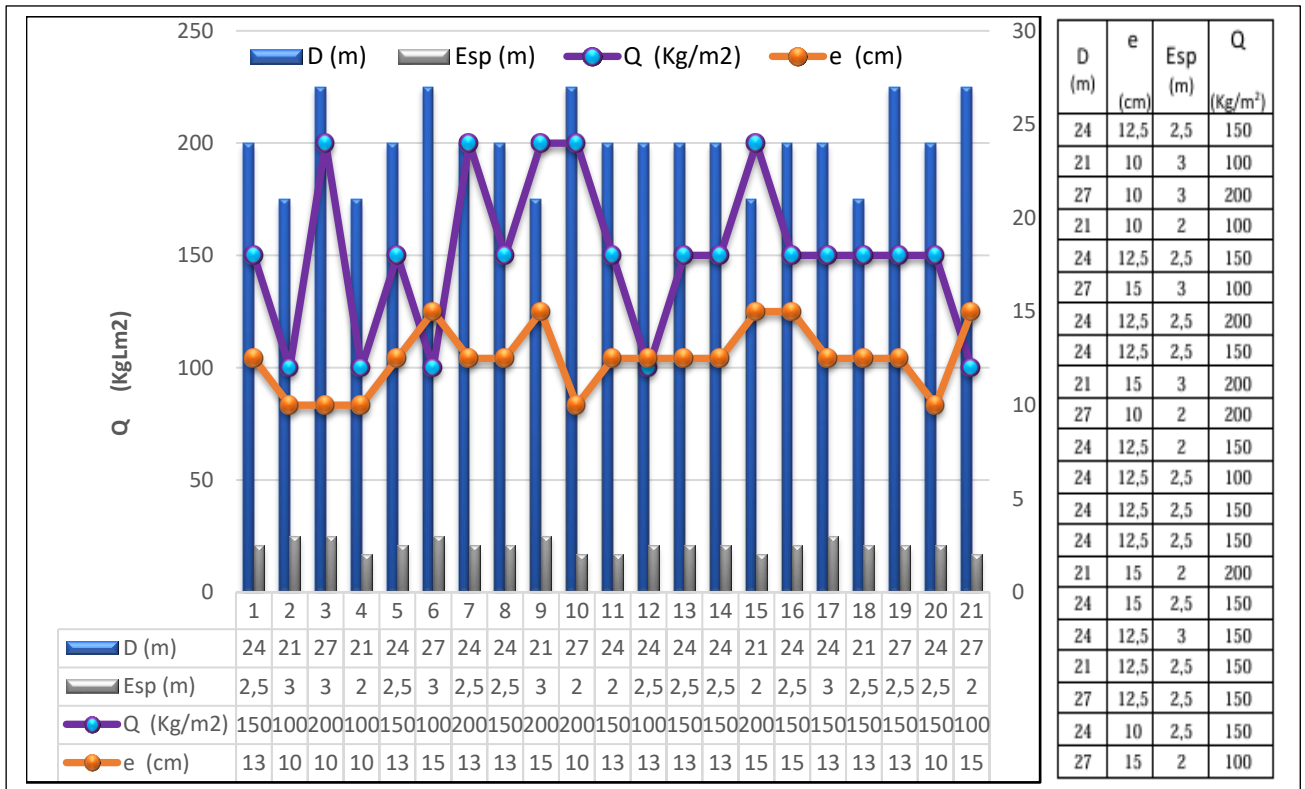


Figure 4: Representation of the experiment matrix, part 1: Variables.

Figure 4 shows a graphical model of all the cases studied, with all the variable parameters. These numerical simulations have been validated to a first approximation. Figure 5 illustrates the mechanical response using a structure weight indicator, showing the linear increase in structure weight as a function of increasing dome diameter. A 29% increase in diameter results in a 64% increase in structure weight, which explains the sensitivity of structure weight to diameter variation.

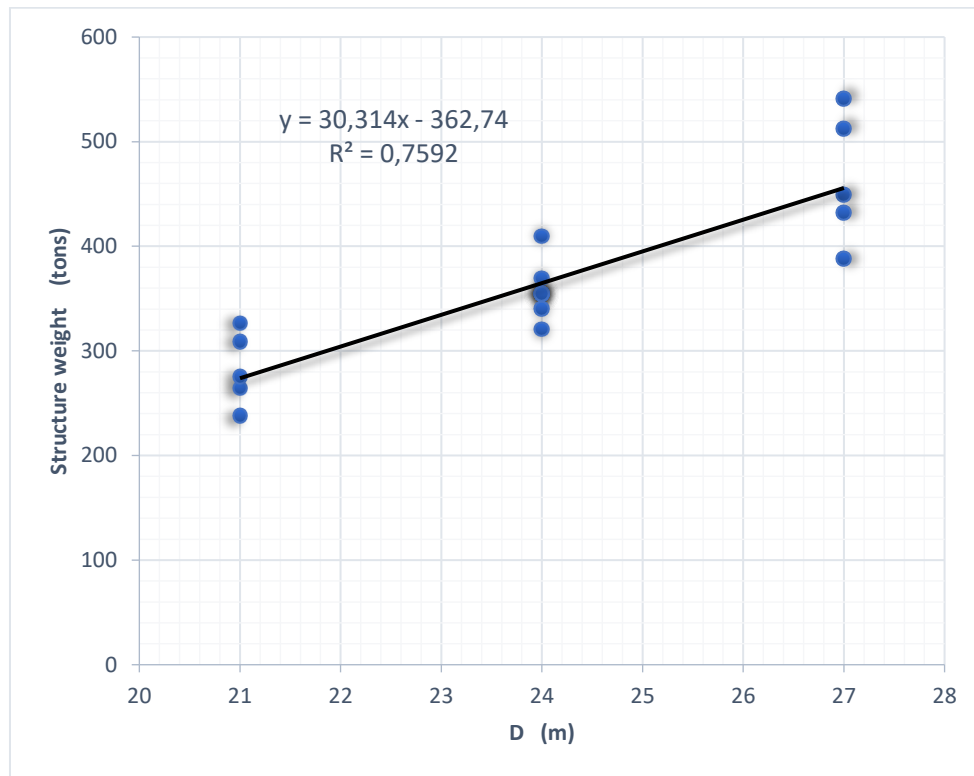


Figure 5: Experience matrix, part 2: Response.

Having characterized the various initial parameters of our study, we will then present, as a second approximation, the curves and graphs grouping the interactions of the data with the final optimization results of the ribbed domes. The optimization work will be elaborated by adopting the design of experiments method, using the Design - Expert 7.0.0 software. The aim of this step is to provide a precise numerical vision of the overall mathematical relationship between the various parameters.

4 Response surface methodology (RSM) and analysis of variance (ANOVA)

In this step, we will simulate the interaction of the various study parameters, using the results obtained in Figures 4 and 5. In our optimization study, we aim to optimize the number of trials and minimize the experimental factors in order to achieve maximum results. The aim of the study is to find out how we can set our parameters in order to get the best response for predicting the objective function. The predictive response models in this study were developed using RSM. The models' reliability was checked using analysis of variance (ANOVA). Response models produced might be linear or higher-degree polynomials as presented in a generalized format in Equations (2) and (3), respectively.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_n X_n + \epsilon \quad (2)$$

$$Y = \beta_0 + \sum_i^k \beta_i X_i + \sum_i^k \beta_{ii} X_i^2 + \sum_{ij}^k \beta_{ij} \cdot X_i \cdot X_j + \epsilon \quad (3)$$

where y denotes the desired response, β_0 is the regression coefficient for the constant term, whereas β_i , β_{ii} , and β_{ij} are the coefficients for linear, quadratic, and the interaction of x_i and x_j terms, respectively. The number of factors is denoted by k , while the random error is denoted by ϵ .

These parameters included dome diameter, dome thickness, rib spacing, and applied load, denoted A, B, C, and D in coded terms, respectively. Each factor value varied over five (5) levels, namely: axial points ($-\alpha$ / $+\alpha$), factor points ($-1/+1$) and central point (0).

ANOVA is a statistical technique utilized to assess the significance and contribution of different factors in explaining the observed variability in responses. The implementation of ANOVA also facilitates the dissection of distinct effects from the variance observed in the measured response. It should be noted that ANOVA analysis was carried out using Expert Design Software 13.

Table 1 and 2 presents a comprehensive overview of the input variables employed in the experimental design, including their coding and corresponding actual levels.

Table 1: Coding and real levels for RSM

Variables	Unit	Symbol	Coded factor levels		
			-1	0	+1
Dome diameter	m	A	21	24	27
Dome thickness	m	B	0.10	0.125	0.15
Rib Spacing	m	C	2	2.5	3
Applied load	(kg/m ²)	D	100	150	200

Table 2: Numerical results

Number of tests	A	B	C	D	Weight of the structural system (Tons)
1	24(0)	0.125(0)	2.50(0)	150(0)	354.94
2	21(-1)	0.10(-1)	3(+1)	100(-1)	238.04
3	27(+1)	0.10 (-1)	3(+1)	200(+1)	388.18
4	21(-1)	0.10 (-1)	2(-1)	100(-1)	308.99
5	24(0)	0.125(0)	2.50(0)	150(0)	354.94
6	27(+1)	0.15(+1)	3(+1)	100(-1)	432.14
7	24(0)	0.125(0)	2.50(0)	200(+1)	354.94
8	24(0)	0.125(0)	2.50(0)	150(0)	354.94
9	21(-1)	0.15 (+1)	3(+1)	200(+1)	264.34
10	27(+1)	0.10(-1)	2(-1)	200(+1)	512.42
11	24(0)	0.125(0)	2(-1)	150(0)	409.50
12	24(0)	0.125(0)	2.50(0)	100(-1)	354.94
13	24(0)	0.125(0)	2.50(0)	150(0)	354.94
14	24(0)	0.125(0)	2.50(0)	150(0)	354.94
15	21(-1)	0.15(+1)	2.00(-1)	200(+1)	326.42

16	24(0)	0.15(+1)	2.50(0)	150(0)	369.55
17	24(0)	0.125(0)	3(+1)	150(0)	320.84
18	21(-1)	0.125(0)	2.50(0)	150(0)	275.38
19	27(+1)	0.125(0)	2.50(0)	150(0)	448.99
20	24(0)	0.10(-1)	2.50(0)	150(0)	340.33
21	27(+1)	0.15(+1)	2(-1)	100(-1)	540.85

ANOVA aimed to describe the individual and combined effects of each factor (dome diameter, dome thickness, rib spacing, and applied load) on the weight of the structural system. The quadratic mathematical model, obtained in terms of a coded factor developed by statistical software (Expert Design, Version 13), is expressed by equation (4).

$$\text{Weight of the structural system (Tons)} = + 354.33 + 86.81A + 14.61B - 45.46C + 3.58AB - 12.49AC + 0.095AD + 3.05BC - 5.17BD - 0.83CD + 8.37A^2 + 1.12B^2 + 11.35C^2 + 1.12D^2 \quad (4)$$

Table 3: Analysis of variance (ANOVA) of Weight of the structural system.

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F	Significance
Model	1.09E+05	14	7780.26	6388.94	< 0.0001	Yes
A-Domediameter	15070.22	1	15070.22	12375.25	< 0.0001	Yes
B-Domethickness	426.9	1	426.9	350.56	< 0.0001	Yes
C-RibSpacing	20669.75	1	20669.75	16973.44	< 0.0001	Yes
D-Appliedload	0	1	0	0	1	No
AB	20.53	1	20.53	16.86	0.0063	Yes
AC	1248	1	1248	1024.82	< 0.0001	Yes
AD	0.014	1	0.014	0.012	0.9168	No
BC	74.42	1	74.42	61.11	0.0002	Yes
BD	42.77	1	42.77	35.12	0.001	Yes
CD	5.54	1	5.54	4.55	0.0768	No
A²	178.76	1	178.76	146.8	< 0.0001	Yes
B²	3.22	1	3.22	2.64	0.155	No
C²	329.04	1	329.04	270.2	< 0.0001	Yes
D²	3.22	1	3.22	2.64	0.155	No
Residual	7.31	6	1.22			
Lack of Fit	7.31	2	3.65			
Pure Error	0	4	0			
Cor Total	1.09E+05	20				
Standard of deviation.		1.1	R-Squared	0.9999		
Mean		364.79	Adjusted R-Squared	0.9998		
Coefficient of variation. %		0.3	Predicted R-Squared	0.9879		
Predicted residual error of sum of squares		1322.89	AdequatePrecision	324.069		

The model F-value of 6388.94 implies the model is significant. There is only a 0.01% chance that a "model F-value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case, A, B, C, AB, AC, BC, BD, A², C² are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Pred R-Squared" of 0.9879 is in reasonable agreement with the "Adj R-Squared" of 0.9998. "Adeq Precision" measures the signal-to-noise ratio. A ratio greater than 4 is desirable. Your ratio of 324.069 indicates an adequate signal. This model can be used to navigate the design space.

From the probability distribution of the experimental values as a function of the predicted values presented in **Figure 6**, we can see that the cloud of responses is very close to the regression line. This indicates that the developed models are adequate in terms of the chosen factors.

Figure 7 reveals that factor A on the positive side (+1) and factor C on the negative side (-1) have a positive influence on the increase in the weight of the structural system. On the contrary, the reverse direction has a negative influence. On the other hand, both factors B and D are slightly increased on the positive side (+1).

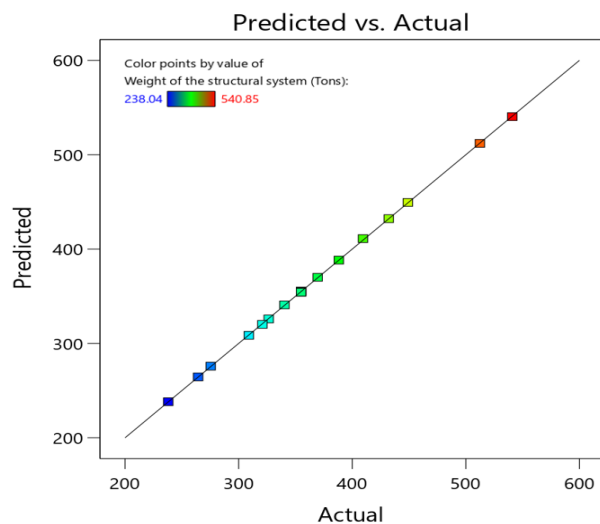


Figure 6: Probability distribution plot for Weight of the structural system.

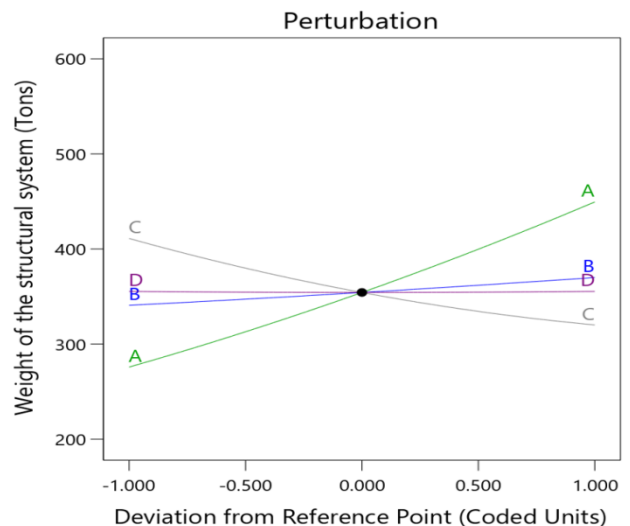
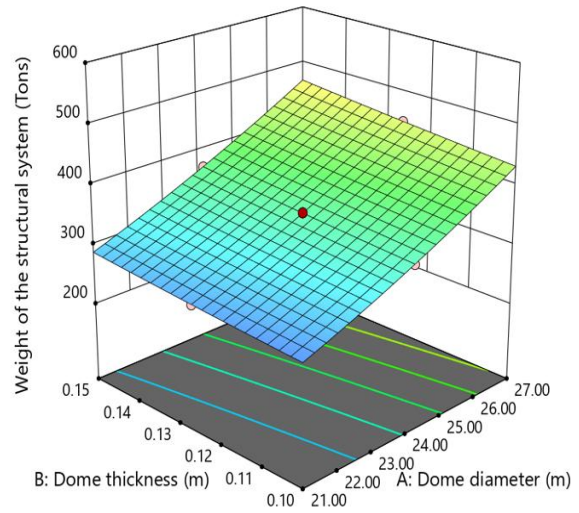
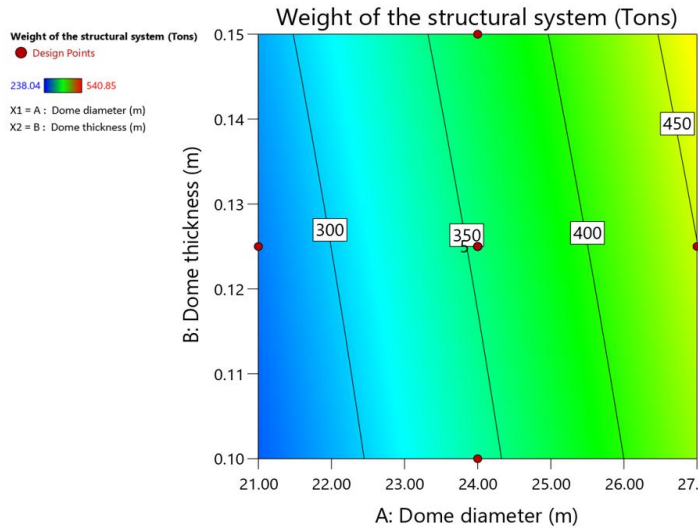


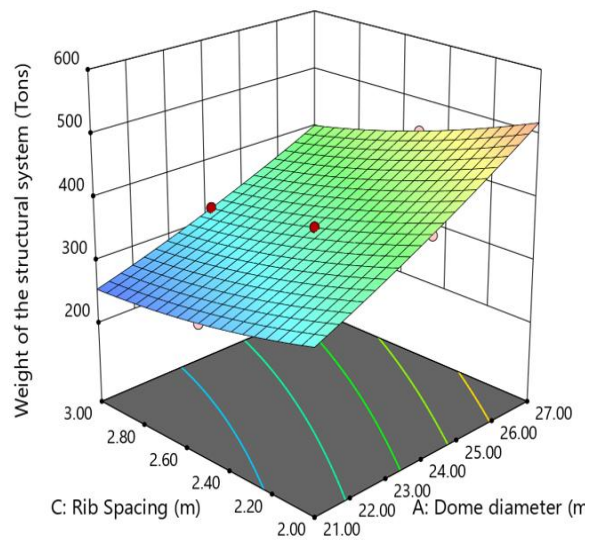
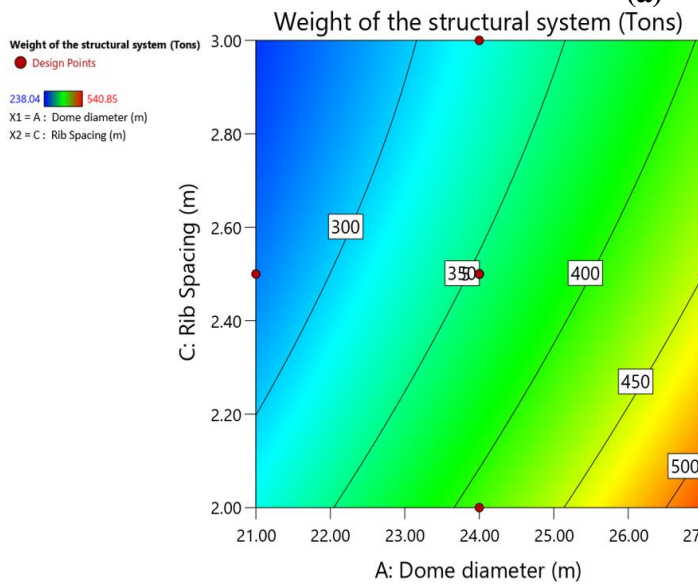
Figure 7: Perturbation plot for Weight of the structural system.

Figure 8 shows that the 2D contour and 3D surface curves are used to visualize the response surface and evaluate any potential interactive relationship. These graphics aim to establish the values of the response variables under study and the desirable operating conditions and can provide a clearer picture of the response surface.

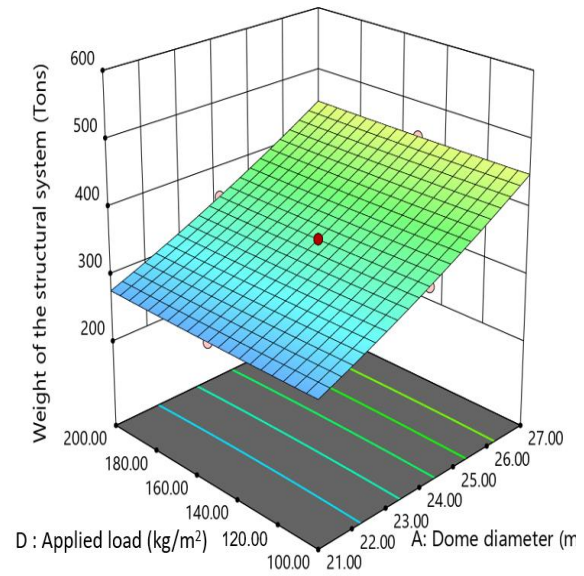
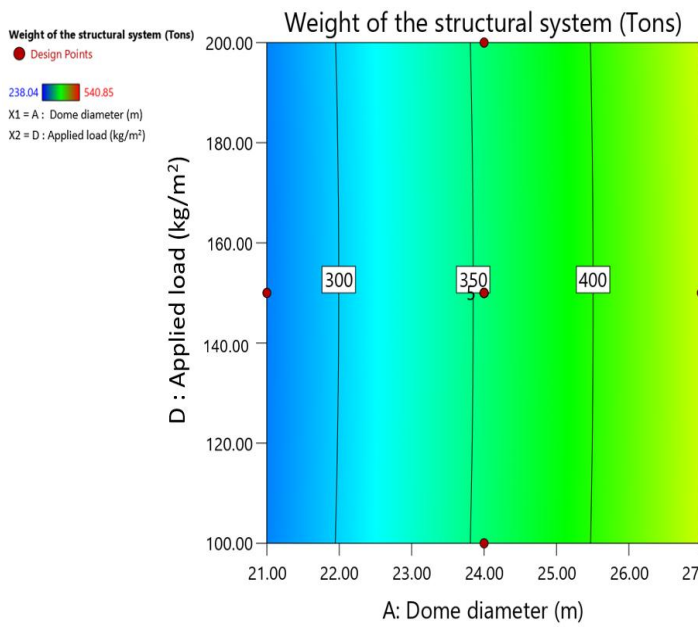
The results obtained from **Figure 8(a)** demonstrate that an increase in diameter of approximately 27 m and a decrease in thickness of the dome of approximately 0.1 m lead to high values of the structural weight of the system (up to 450 t). As shown in **Figure 8(b)**, it is also clear that an increase in the dome's diameter by approximately 27 m and a decrease in rib spacing by about 2 m result in an increase in the structural system's weight values (up to 500 t).



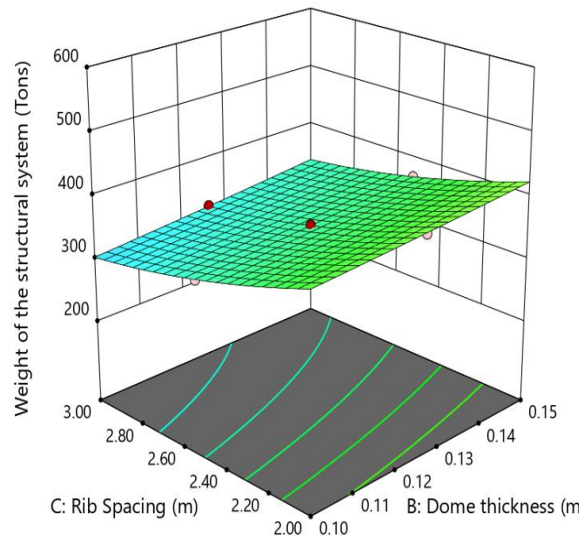
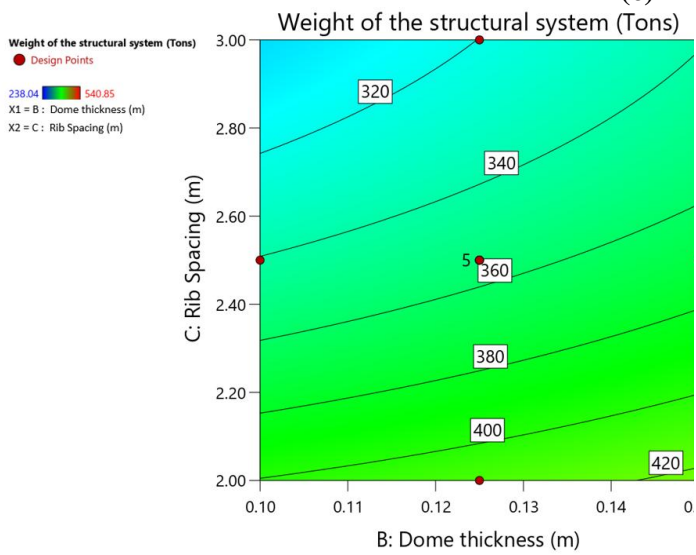
(a)



(b)



(c)



(d)

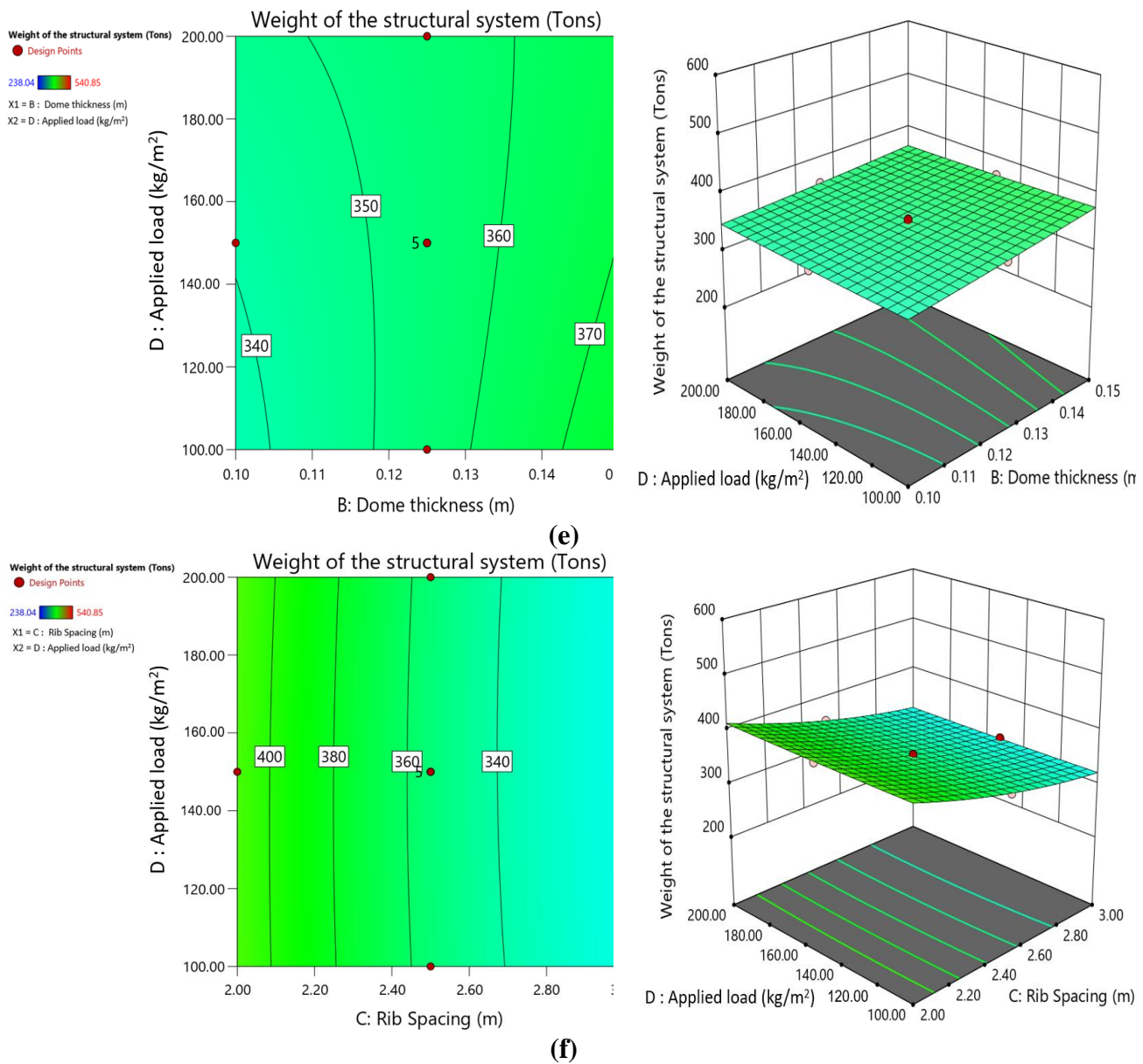


Figure 8: RSM analysis diagrams for Weight of the structural system.

According to **Figure 8(c)**, high values of the structural system's weight (up to 400 tonnes), were obtained with a dome diameter of approximately 27 m. However, the applied load is nearly constant, even though it varies between 100 and 200 kg/m². Based on response surface plots presented in **figure 8(d)**, high values of the structural system weight (up to 420 tonnes), were obtained with a dome diameter of approximately 27 m. On the other hand, the thickness of the dome remains almost constant, even though it varies between 0.1 and 0.15 m. The results obtained from **Figure 8(e)** demonstrate that an increase in the thickness of the dome by approximately 0.15 m, leads to low values of the weight of the structural system (up to 370 tonnes). On the other hand, the applied load remains almost constant, even if it varies between 100 and 200 kg/m². As shown in **Figure 8(f)**, demonstrate that a decrease in rib spacing by

approximately 2 m, leads to an increase in the values of the weight of the structural system (up to 400 tons). On the other hand, the applied load remains almost constant, even if it varies between 100 and 200 kg/m². We also note that the key parameter of the structural system is the diameter of the dome, the other parameters do not have a direct significant influence on the mechanical response of the system. Other studies [4], [5], [18] have confirmed the same behavior.

5 Optimization of results

To improve the functional relationships between variables (factors) and responses, optimization analysis was conducted using the established mathematical model to determine the optimal values for dome diameter, dome thickness, rib spacing, and applied load. This optimization process is necessary because it involves the simultaneous evaluation of different responses. The optimization standards for the structural system's weight are detailed in **Table 4**.

Table 4: Optimization standards of individual responses for Weight of the structural system (Tons).

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A : Domediameter	Maximize	21	27	1	1	3
B : Domethickness	Maximize	0.1	0.15	1	1	3
C : RibSpacing	Minimize	2	3	1	1	3
D : Appliedload	Maximize	100	200	1	1	3
Weight of the structural system (Tons)	Maximize	238.04	540.85	1	1	3

We used a multi-objective numerical optimization approach to determine the optimal parameters, such as the dome diameter, dome thickness, rib spacing, and applied load, in order to maximize the weight of the structural system. The primary objective of this optimization study was to identify the ideal values of the independent variables to achieve the optimization goals. To enhance the response, the RSM technique was employed since these responses were influenced by multiple variables. The summary of the optimal solutions obtained using the RSM method is presented in **Table 4**. The most favorable optimal solution, corresponding to trials 1 to 6, was 0.993598. Each optimization method was designed based on the importance or weight assigned to each factor. **Figure 9** illustrates solution 1 out of 87.

The **figure 10** presents the graphical representation of the optimized responses. It highlights that the optimal parameters for multi-objective optimization of the results are as follows: a dome diameter of 27 m, a dome thickness of 0.15 m, rib spacing of 2 m, and an applied load of 199.77 kg/m². The optimal weight of the structural system amounts to 531.963 tons. In this study, the response in terms of the weight of the structural system has been identified as the primary research objective, and the optimal solutions have shown an opportunity of 0.994.

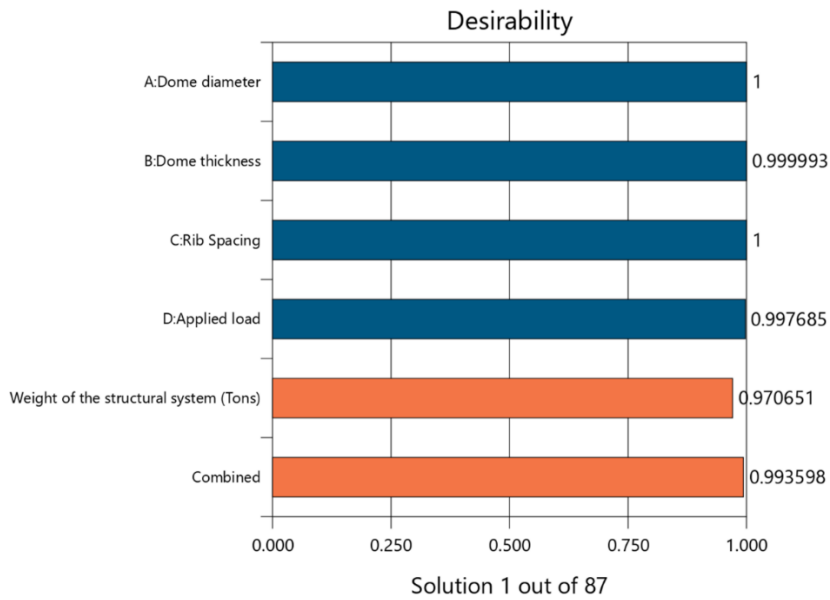


Figure. 9: Optimization solution 1 out of 87.

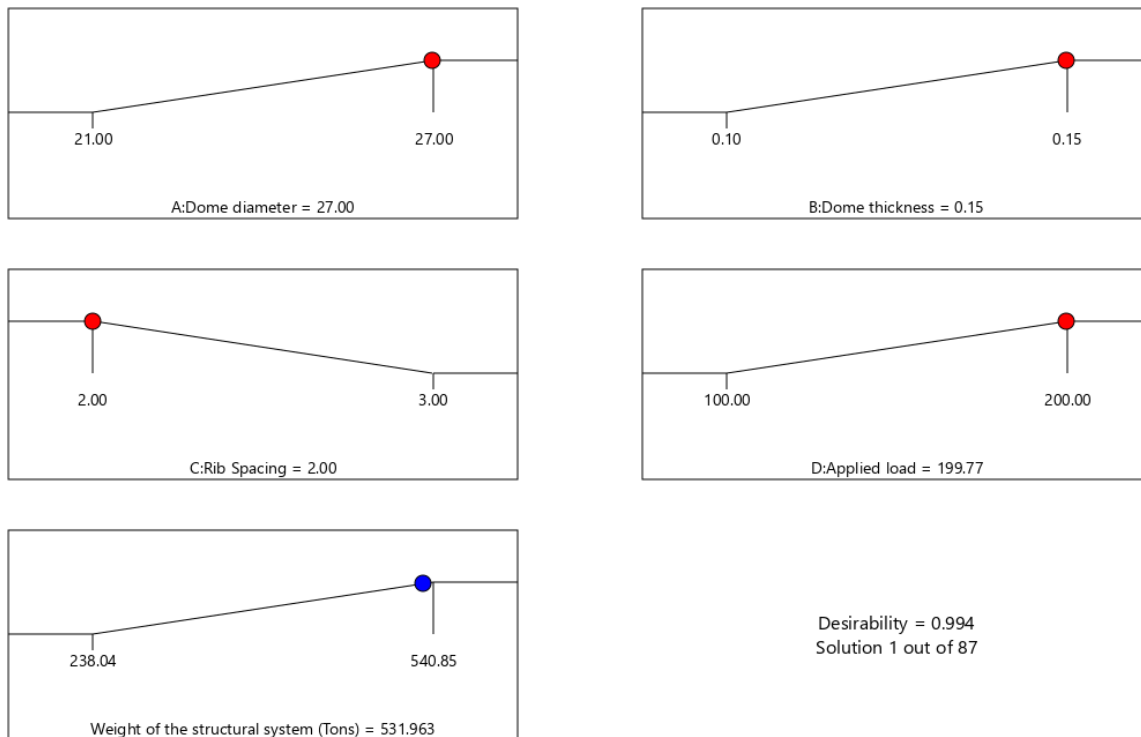


Figure. 10: Numerical optimization ramps with desirability 0.994 and solution 1 out of 87.

The model (formula 4) will be definitively validated with a numerical simulation calculation, losing an example of an intermediary case that does not appear in the matrix of experiments.

Consider a dome with meridian ribs, with geometric characteristics of the structural system as follows: $D = 21.5$ m , $e = 11.7$ cm, $E_{sp} = 2.85$ m. The weight of the dome using optimization formula (3) is : $P = 264.67$ t. The dome weight using numerical simulation is $P = 260.29$ t. This represents a model deviation of the order of 1.7%, a very close approximation. The usefulness of the model resulting from the global approach is to obtain a direct and rapid answer concerning an objective function, which reflects a targeted economic aspect. This function satisfies the constraints and conditions laid down at the start of the problem. The designer is thus faced with a rapid technical choice, according to the design parameters available, without having to go through the tedious verifications of the optimization problem.

6 Conclusion

Starting with a structural system of meridian-ribbed domes that represents an economical solution for covering large spaces, and going through several optimization approximations, the approach proposed in this article has given satisfaction. The proposed model can provide the designer and builder at the same time with the optimum solution for such a structural system, and its usefulness lies not only in its simplicity, but also in the fact that the constraints of the problem and the optimization conditions do not appear in the objective function, which makes the task much easier. The work carried out in this article presents an approach aimed at targeting the main stages that need to be the subject of a global optimization, which cannot be of use to either the designer or the builder, without taking into account mechanical performance linked directly with economic concerns. It is important to point out that, although the scope of this study remains narrow, the reference diameter of the cases studied is between 21 and 27 m, but the principle of the proposed approach remains the same, and can serve as a guide to widening the scope of validation of the study in subsequent research.

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